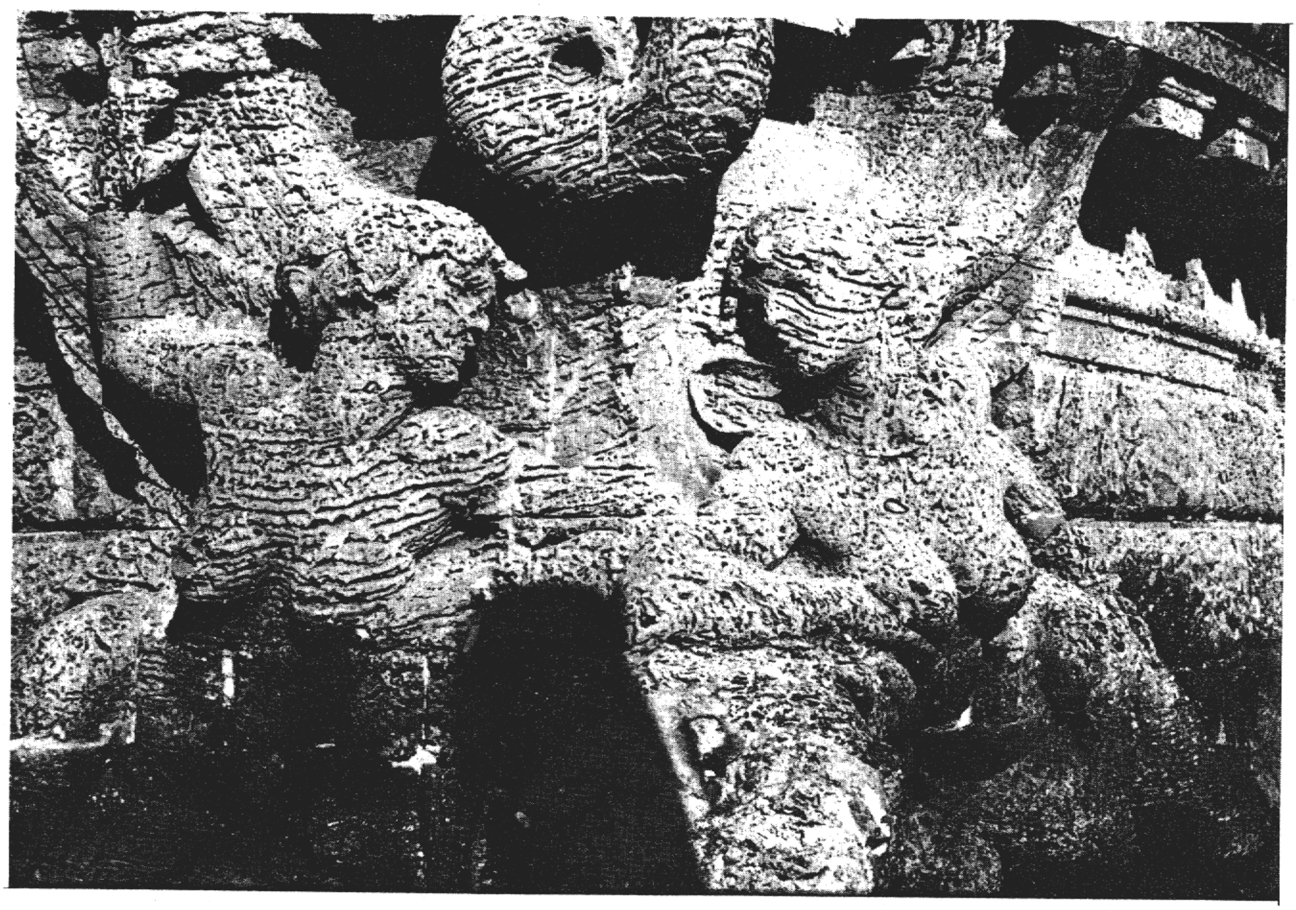
THE MIAMI LIMESTONE

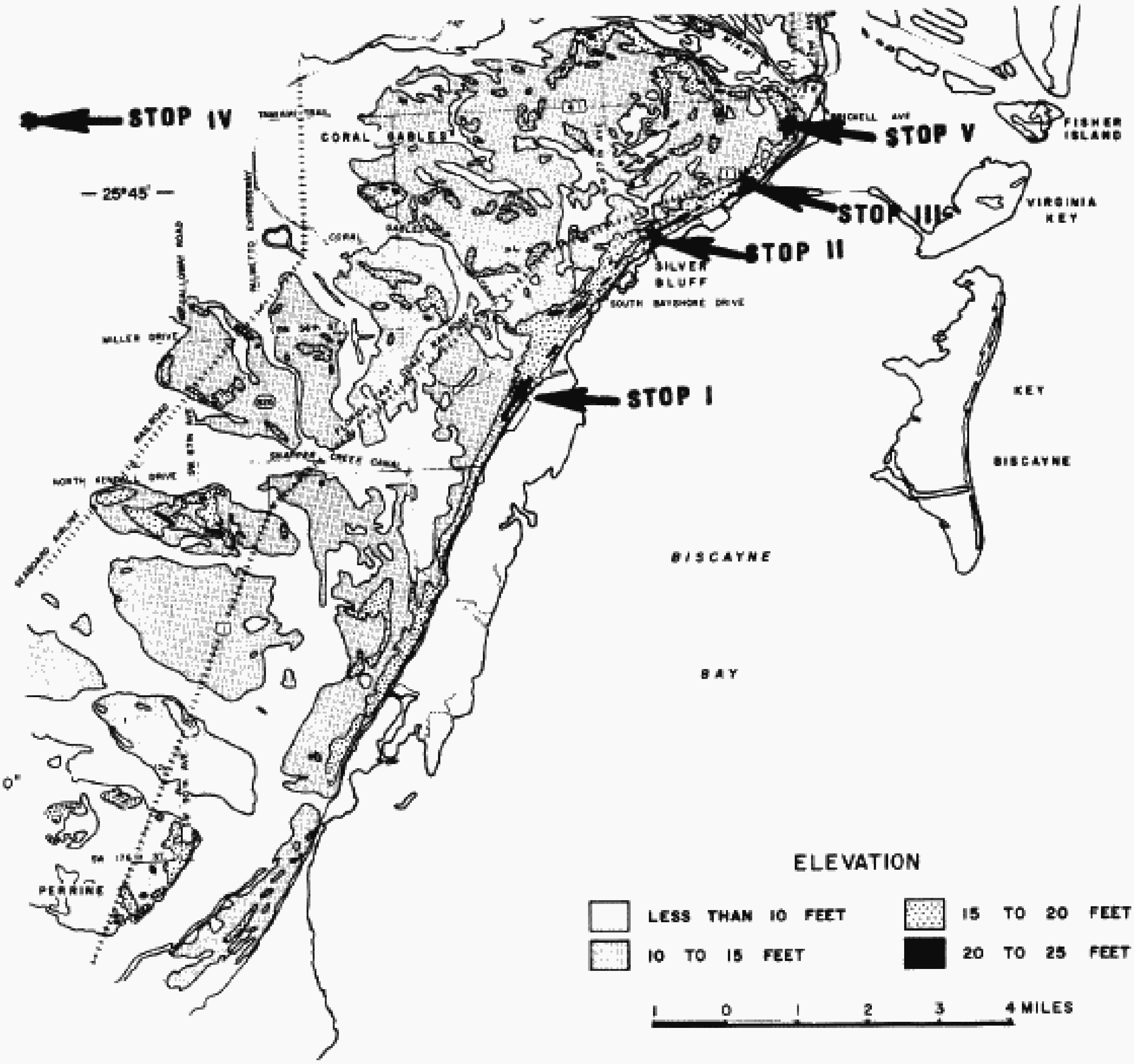
A Guide to Selected Outcrops and Their Interpretation

(WITH A DISCUSSION OF DIAGENESIS IN THE FORMATION)



by Robert B. Halley and Charles C. Evans

MIAMI GEOLOGICAL SOCIETY
1983



Field stop locations shown relative to topography (after White, 1970).

Cover photograph: Miami Limestone maidens; left torso - crossbedded facies; right torso - burrowed facies. Venetian boat dock, Vizcaya Museum, Miami.

Table of Contents

	Page
Preface	ii
Acknowledgements	ii
Introduction	1
Age and stratigraphic setting	1
Facies anatomy	4
Modern analogs and topography	6
Hydrologic considerations	9
Field Stops	
STOP I: Active ooid sand shoal	17
Bounding surfaces and other sedimentary structures	18
Diagenesis	31
STOP II: Sea cliff exposing channelled bar	35
Channels	35
Silver Bluff	35
STOP III: Seaward stabilized sand flat	42
STOP IV: Platform interior sands and the base of the Miami Limestone	45
Miami Limestone boulders	45
Older limestone boulders	46
STOP V: Islands on the shoals	49
Significance of diagenesis within the Miami Limestone	55
Summary	59
References cited	60
Appendix I: Historical summary	64
Appendix II: Additional stops	66
Appendix III: Estimate of surface dissolution	67

PREFACE

Exposures of the Late Pleistocene Miami Limestone in Dade County provide unexcelled localities at which to view the depositional and early diagenetic features of an ooid shoal complex. Each year hundreds of geologists and geology students make the pilgrimage to the modern carbonate depositional environments of south Florida. Often these groups spend a few hours of their trip viewing the Pleistocene limestones of the Miami area. This volume is written to serve as a field guide to several of the most frequently visited localities. The guide brings together information from diverse sources that bears on the interpretations made from these outcrops, and allows us to vent some of the observations and ruminations on this formation which we have accumulated over several years of studies.

This guidebook is principally designed as a one-day field trip for a group of about 50 people. Rather than present the users of this book with a great many field stops, we have selected five stops which we believe illustrate the main features of the formation and which will serve as vehicles for discussion of depositional and diagenetic principles while in the field. Included in an appendix to the body of the text are a number of additional stops for those having both time and a desire to see some of the lesser known, but still important, exposures of the Miami Limestone.

We hope this guide will answer some of the questions which are raised by the features observed in outcrop and, more importantly, encourage new thinking and further study on the many problems which remain.

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Undoubtedly we have picked up many ideas from casual comments during field trips with U.S. Geological Survey or American Association of Petroleum Geologists groups since 1974. For those who have contributed anonymously and perhaps unknowingly, thanks. Appreciation is extended to Barbara Lidz for her editorial expertise.

INTRODUCTION

Exposures of the Miami Limestone in Dade County, Florida, exhibit outstandingly well preserved sedimentary and diagenetic features of a subaerially exposed ooid sand body. During this field trip, we will be able to make observations at each outcrop that are fundamental to developing an overall interpretation of the Miami Limestone. We will also be able to make useful comparisons between the now fossil Miami ooid system and modern ooid systems in the Bahamas by noting both the similarities and the differences in the morphology, sedimentary structures, and diagenetic products of these Floridian and Bahamian deposits. For a more general treatment of the Quaternary history of south Florida, readers are referred to John E. Hoffmeister's (1974) excellent volume <u>Land From the Sea.</u>

Before we begin our examination of the Miami Limestone, a certain amount of background information is helpful. The next few pages summarize portions of the published literature which pertain directly and indirectly to the Miami Limestone. Although this is by no means an exhaustive summary, it provides field trip participants with a "baseline" understanding of the Miami Limestone for use in the field. These topics include: 1) age and stratigraphic setting; 2) facies anatomy; 3) modern analogs and topography; and 4) hydrologic considerations.

Age and Stratigraphic Setting

The Miami Limestone forms the bedrock in the Miami area (fig. 1) and is late Pleistocene in age. We follow the terminology of Hoffmeister and others (1967) who combined the Miami Oolite and equivalent pelloidal facies forming the Miami Limestone. A brief historical review of the nomenclature for the unit and a stratigraphic column are provided in Appendix I. The formation is the youngest marine Pleistocene deposit in the area, but is overlain by a thin quartz sand layer which may be a southward extension of the Holocene Pamlico Formation (DuBar, 1974). The quartz sand fills solution holes in the Miami Limestone and may be as much as 1 meter (3 feet) thick in topographically low areas.

The base of the Miami Limestone (fig. 2) is generally picked at a significant lithologic break which represents a period of subaerial exposure during a lowering of sea level (STOP IV). This break in deposition occurs at the top of the Fort Thompson Formation, a unit that contains several similar diastems within it. Perkins (1977) interpreted a sharp contact between the cross-bedded facies and burrowed facies of the Miami Limestone to be a subaerial exposure horizon. We, however, concur with the earlier interpretation of Hoffmeister and others (1967) that this facies contact is an unusually sharp marine facies boundary. (This contact is discussed in detail at STOP I).

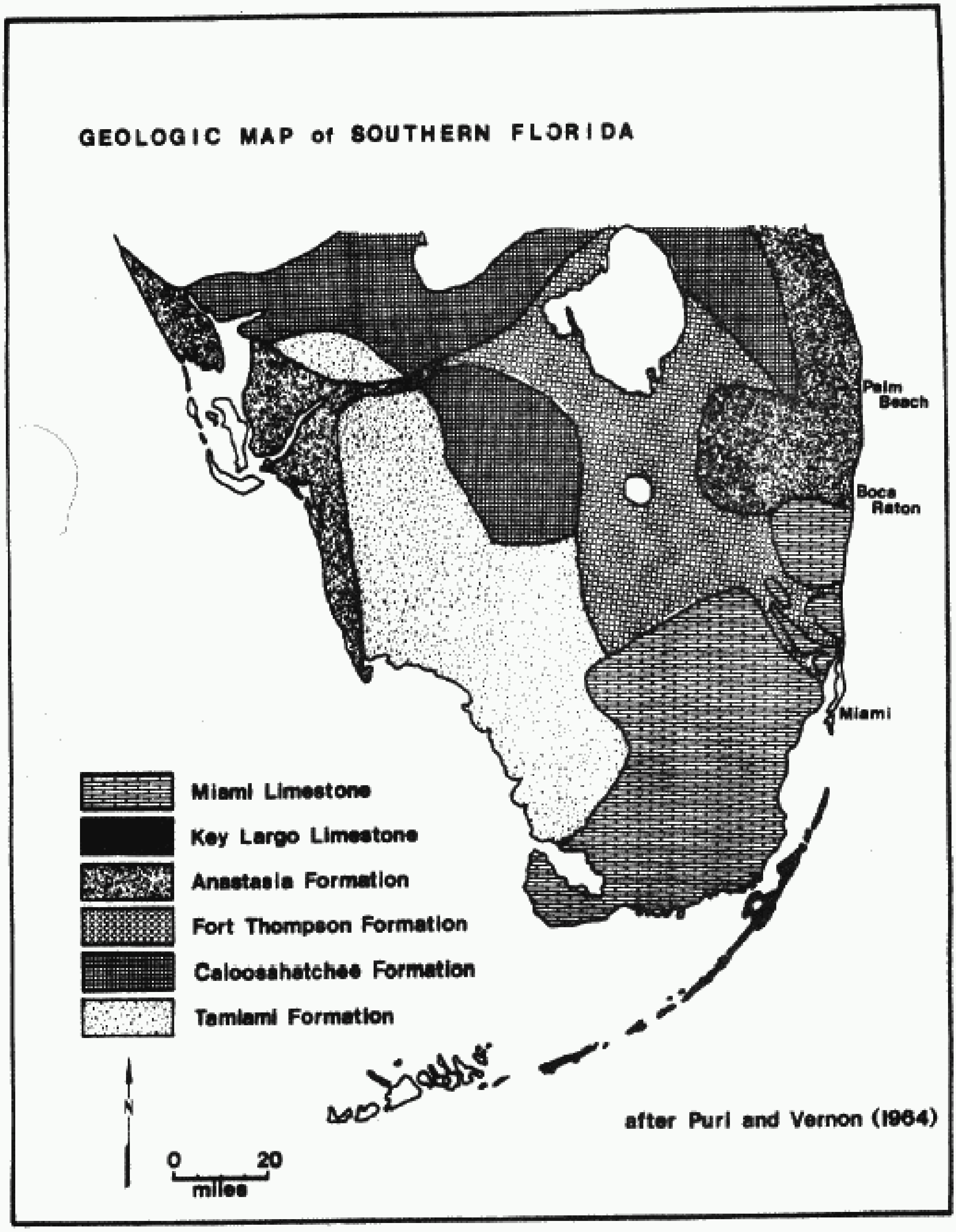


Figure 1. A geologic map of southern Florida (after Puri and Vernon, 1964). The map shows the vast areal extent of the Miami Limestone (brick pattern) on mainland Florida. We recognize the oolite of the lower Florida Keys (shown in white) to be part of the Miami Limestone.

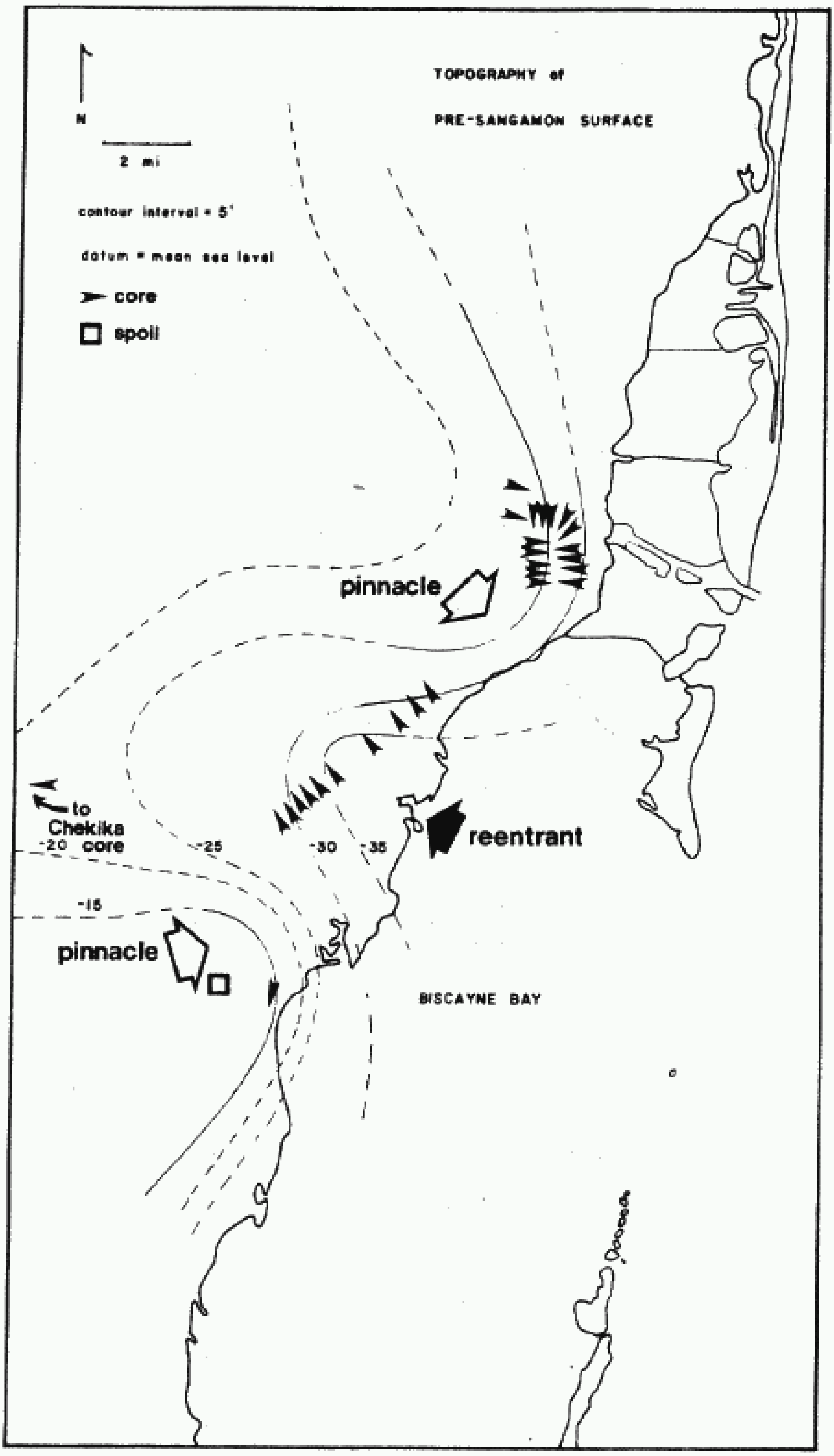


Figure 2. Base of the Miami Limestone (from Evans, 1982).

Oolite samples from the Miami Limestone were among the first Pleistocene limestone samples to be dated by the uranium-series dating method. The results of this work led Osmond, Carpenter, and Windom (1965) and Broecker and Thurber (1965) to conclude that the Miami Limestone and the uppermost portion of the Key Largo Limestone are contemporaneous deposits about 130,000 years old. Continued study of Pleistocene limestones throughout the Caribbean Sea indicates that the Miami Limestone is coeval with deposits on Barbados (Terrace III, Mesollela and others, 1969), the main terrace of La Orchila (Schubert and Szabo, 1978), and limestones in the Bahamas (Neumann and Moore, 1975). Coralline limestones of similar age have been found along the coast of the Yucatan Peninsula (Szabo and others, 1979) and as far away as New Guinea (Chappell, 1974). These deposits are now thought to be the record of an interglacial sea-level high stand, about 6.5 m (20 ft) above present sea level. This worldwide event is documented by the oxygen isotopic content of foraminiferal calcite in deep-sea cores and corresponds with the isotope stage 5e of Shackleton and Opdyke (1973). As suggested by Broecker and others (1968) and Neumann and Moore (1975), present day sea level is the highest which has occurred since the deposition of the Miami Limestone (fig. 3). Although Parker and others (1955) and Fairbridge (1974) postulated a 1 to 2 meter sea-level highstand about 2,000 years ago, most geologists agree that sea level in the Miami area has not been higher than its present level during the Holocene. Sea-level rise during the last 5 to 10 thousand years has been documented by a variety of methods from localities around the Caribbean, Gulf of Mexico and Bermuda (fig. 4). There are no documented Holocene, submarine sediments above high-tide level in the Miami area. Wanless (1982) has recently presented evidence that relative sea level is still rising in the Miami area.

Facies Anatomy

The Miami Limestone may be divided into three distinct facies: the bryozoan facies, the bedded facies, and the mottled facies (Evans, 1983). The bedded and mottled facies are confined to the topographic high of the Atlantic Coastal Ridge, where these two facies are commonly seen to alternate in vertical section (Evans, 1982), and the bryozoan facies is confined to the low-lying area to the west of this ridge. The bryozoan facies does not, as reported by Hoffmeister and others (1967), underlie the Coastal Ridge (Evans, 1983). This revised facies anatomy of the Miami Limestone is significant in the interpretation of the depositional history of this unit in that it is clear that 1) the portion of the Miami Limestone which was an active ooid system (the Atlantic Coastal Ridge) originated and grew in place and did not migrate bankward over the platform interior deposits of the bryozoan facies under the influence of the transgressing sea, and 2) the bryozoan facies was deposited as the direct result of the growth of the bathymetric high to seaward, which created the sheltered conditions necessary for the development of the platform interior bryozoan facies (Evans, 1983).

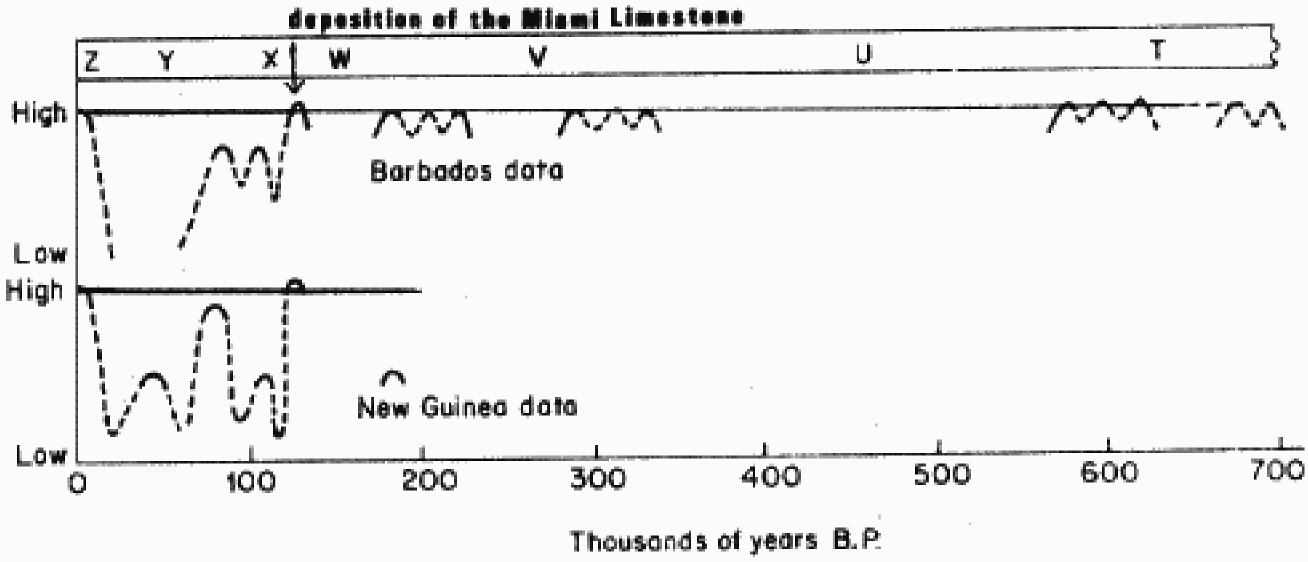


Figure 3. Sea-level fluctuations during the late Quaternary as recorded from Barbados and New Guinea showing the 120,000 yr highstand during which the Miami Limestone was deposited (after Matthews, 1974).

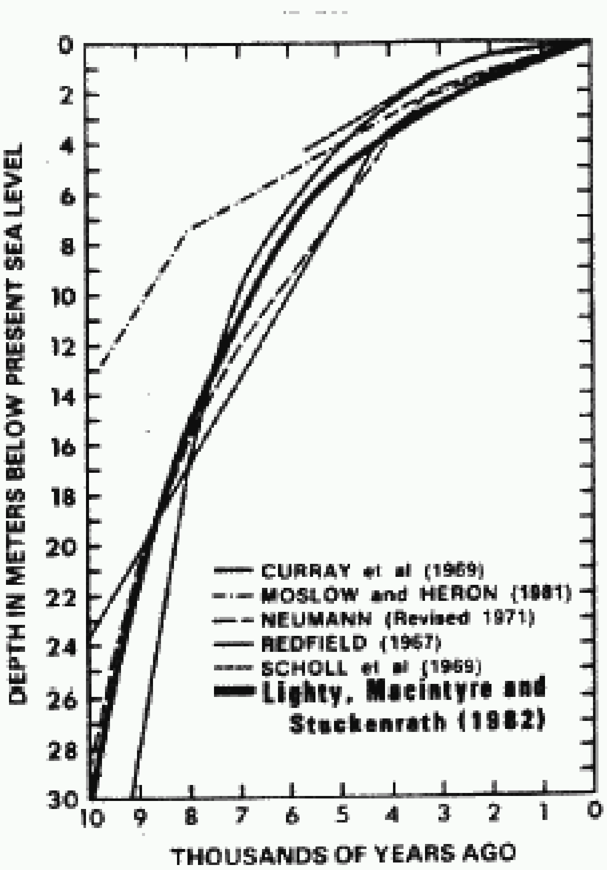


Figure 4. Holocene sea-level rise as recorded in the Atlantic (after Lighty and others, 1982).

Modern Analogs and Topography

Studies of modern ooid shoal areas of the Bahamas provide modern comparisons for the Miami Limestone. Only about a dozen such studies exist. These include Illing (1954), Ball (1967), Imbrie and Buchanan (1965), Bathurst (1967), Imbrie and Purdy (1962), Hine and others (1981) and Hine and Neumann (1977), which include studies of ooid sands as part of more general carbonate sand studies. Works which focus on ooid sands are published by Newell and others (1960), Purdy (1961), Hine (1977), and Harris (1979). Unpublished studies by Buchanan (1970) and Dravis (1977) also add substantially to our understanding of ooid sand complexes. These studies concentrate on grain size, texture, composition, diagenesis, and areal distribution (in three dimensions as revealed by sediment coring). Published, quantitative data concerning the origin of current-formed sedimentary structures in ooid sands are very rare, an exception being information gathered by Imbrie and Buchanan (1965). Much of this information has been recently summarized by Halley and others (1983).

Although modern ooid shoals and the Miami Limestone share many similarities, in detail each is distinct and derives its unique properties from the local peculiarities of its setting. Similarities include proximity to a shelf break, general water depths, grain composition, size and texture, associated fauna and flora, island development, and diagenetic processes. Distinct differences between ooid shoal complexes may be documented in a variety of shoal orientations and geometries which are controlled by local variations in hydrology and pre-existing topography.

On the Atlantic Coastal Ridge the Miami Limestone retains topography that is characteristic of ooid shoals separated by tidal channels. This interpretation of the topography in the Miami area was presented by Hoffmeister and others (1967) with a refinement by Halley and others (1977) who recognized a morphological feature similar to a barrier bar along the northeastern edge of the Pleistocene ooid shoal complex. These features are illustrated in Figure 5. Representative photomicrographs from several areas associated with these features are shown in Figure 6.

The degree to which present-day topography has been modified by weathering during subaerial exposure is a much disputed topic. The pattern of high ooid shoals separated by deeper tidal channels with long orientations approximately normal to the shelf break is clearly preserved southwest of Miami (fig. 5). The shoals are broader than those of modern analogs with limestone exposed at the surface. In contrast, the tidal channels, topographic low areas termed "glades," contain up to 2 meters of quartz sand-rich soil above bedrock. The topography of the area may be less than it was at the time of deposition because rock has been weathered from the topographic high areas, and the low areas have been partially infilled by sand and soil.

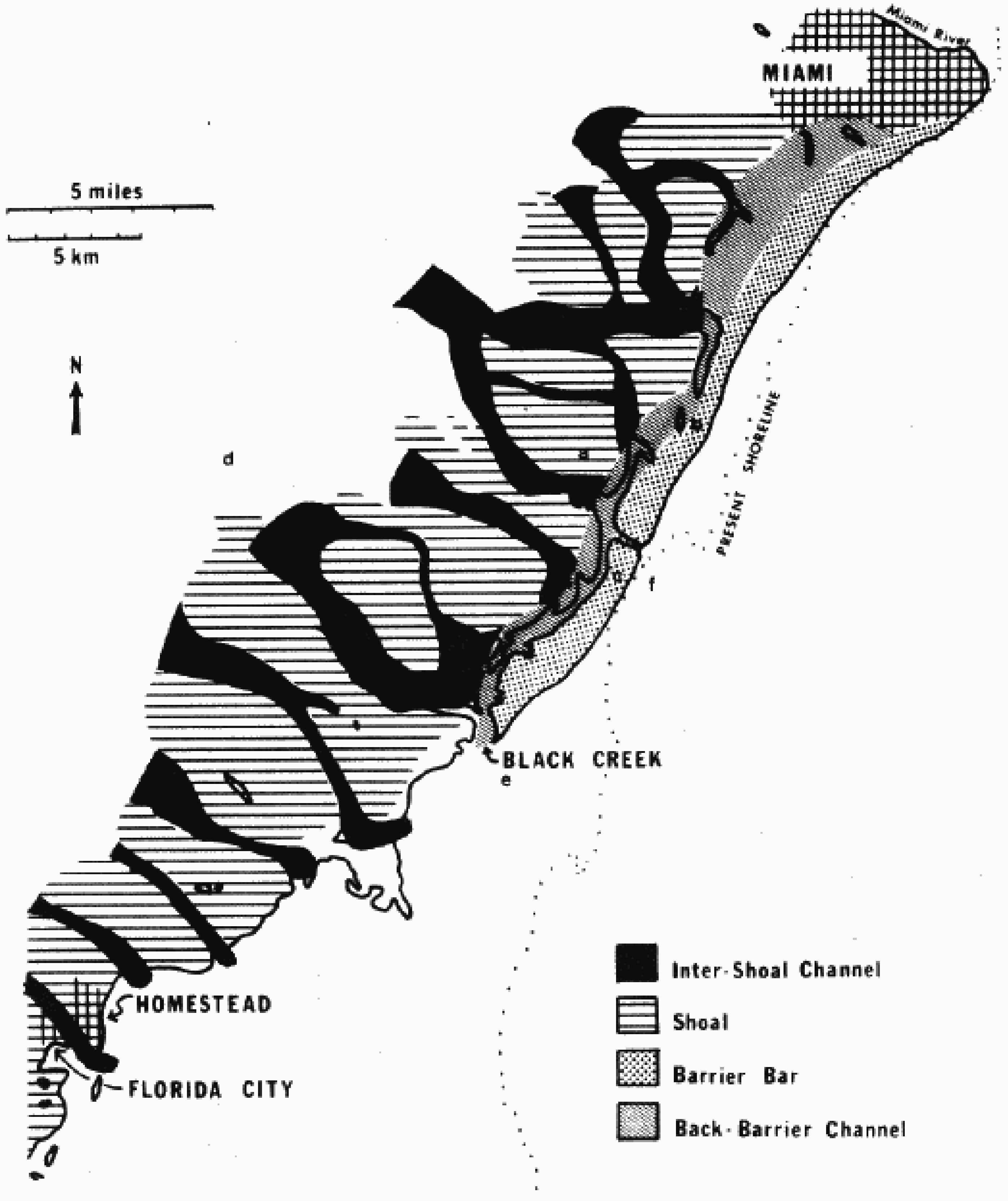


Figure 5. Paleogeographic reconstruction of Pleistocene ooid shoal complex based primarily on present topography; lower case letters indicate position of samples illustrated on Figure 6.

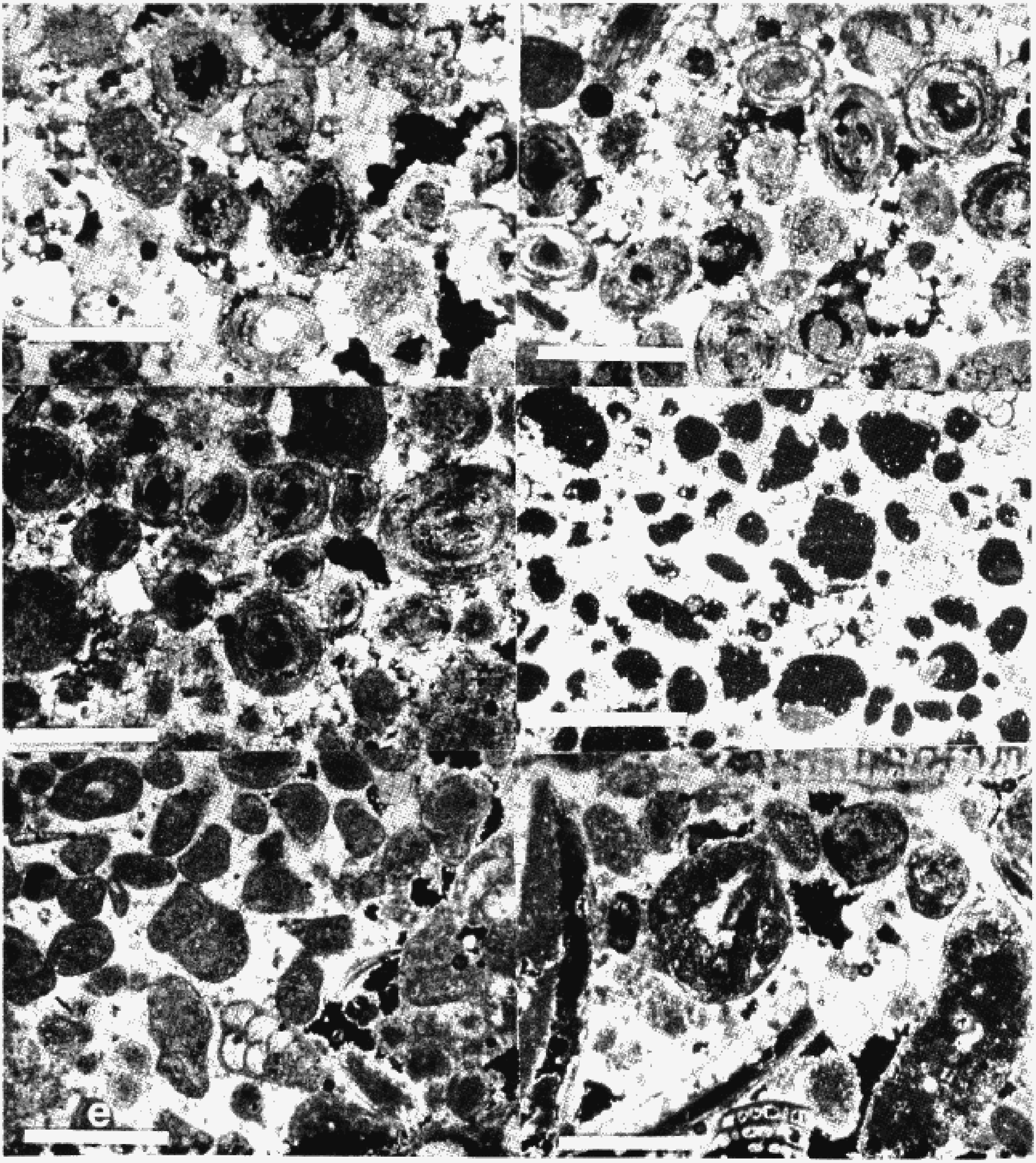


Figure 6. Photomicrographs of Miami Limestone lithologies. a) ooid grainstone of tidal bars; b,c) ooid grainstones of the barrier bar; d) molds of former pelloids from the "bryozoan facies" of Hoffmeister and others (1967); e,f) skeletal and pelloidal grainstones east of barrier bar. Samples are located on Figure 5 by lower case letters. Scale is 500 microns.

The Miami Limestone has certainly been affected by karst dissolution, but this process has not obscured original depositional topography. Most karst features are of only local extent. The most striking exception is Arch Creek north of Miami (fig. 7), which was once crossed by a natural span of Miami Limestone. A small but similar creek flows through the only break in the barrier bar near Old Cutler Road and 162nd Street. Here both sides of the creek are lined with eroded blocks of limestone, which have preferentially dissolved along crossbeds and burrows to develop spectacular vuggy porosity. Sink holes more than 3 meters deep are uncommon in the Miami Limestone but have been found in excavations for building foundations and occur along the extent of the barrier bar. Most are sand-and soil-filled. Sinks almost this deep may be seen along the walkway at Monkey Jungle (additional Stop 14, Appendix II). Solution pits less than 1 meter deep are common throughout the area and cover much of the limestone west of the ooid shoals below elevations of 2.5 meters. Over large areas of the Everglades, dissolution has resulted in a pinnacled surface, typically with about 50 cm of relief.

The thickness of limestone removed by dissolution from the surface is not easily determined. The preservation of shoal and channel morphology suggests that the removed thickness is less than a few meters. The original topographic relief in the area was probably less than 10 meters, based on comparison with modern analogs, and at least 8 meters are still present. Loss of more than a few meters of limestone from the surface probably would obscure relict topography. Although the amount of surface dissolution clearly varies from place to place, it is our belief that average surface removal has been on the scale of about one meter. This estimate is in agreement with calculated estimates (see Appendix III).

Hydrologic Considerations

The Miami area receives an average of about 150 cm of precipitation each year. Dry and wet years have ranged from 48 to 135 percent of normal precipitation. The rainfall is highly seasonal, with 2/3 to 3/4 occurring from May through October. During the rainy season, thunderstorms bring torrential rains that may drop as much as 50 cm of rainfall in 24 hours. These rainfalls are often extremely localized and flooding is greatly reduced because they cover a relatively small area and because the Miami Limestone is extremely permeable. Rainfall is so localized that gauges at Miami and Miami International Airport (8 km apart) occasionally record monthly differences of 25 cm (Parker and others, 1955).

Such rapid rainfall causes marked local changes in the water table. Figure 8 shows a water table response of almost two meters (5.7 ft) during two rainfalls near the Miami International Airport between April 15 and 17, 1942. In addition to water table fluctuations with individual rainstorms, yearly fluctuations of about a meter are common through the rainy and dry seasons (fig. 9). Even larger fluctuations approaching 3 meters in the water table occur during variations from wet years to dry years (fig. 10). Thus the position of the water table for any geologically meaningful length of time becomes rather difficult to identify. It is presumed that in addition to these fluctuations there has been a general rise of the water table associated with the general rise of sea level during the last 5,000 years, but the relationship between sea

Figure 7. The natural bridge at Arch Creek approximately eighty years ago. The bridge collapsed in 1974. (Photograph courtesy of the Historical Association of Southern Florida.)

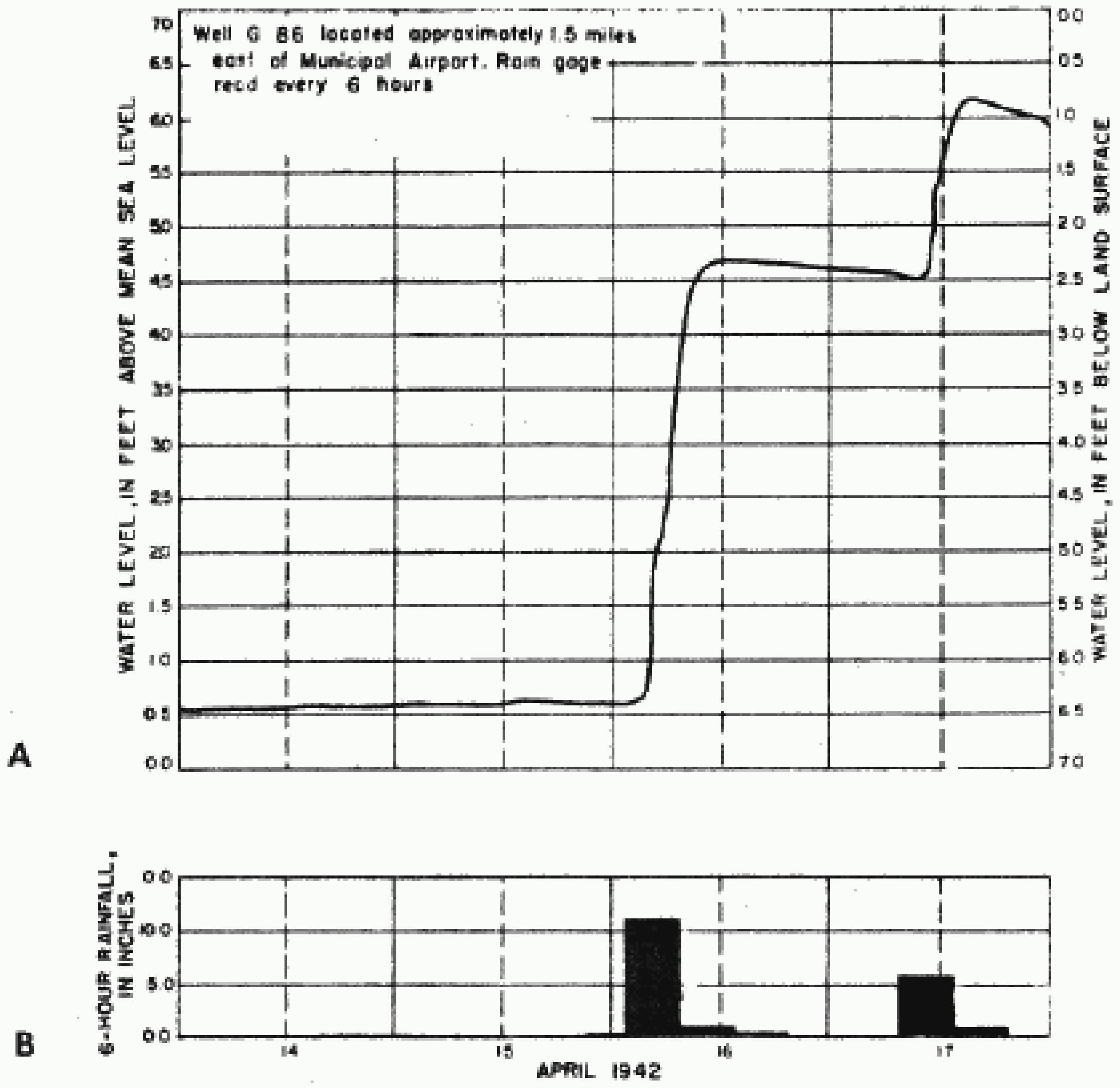


Figure 8. Water table rise (A) in response to two rainfalls (B) during April 16 and 17, 1942 (from Parker and others, 1955).

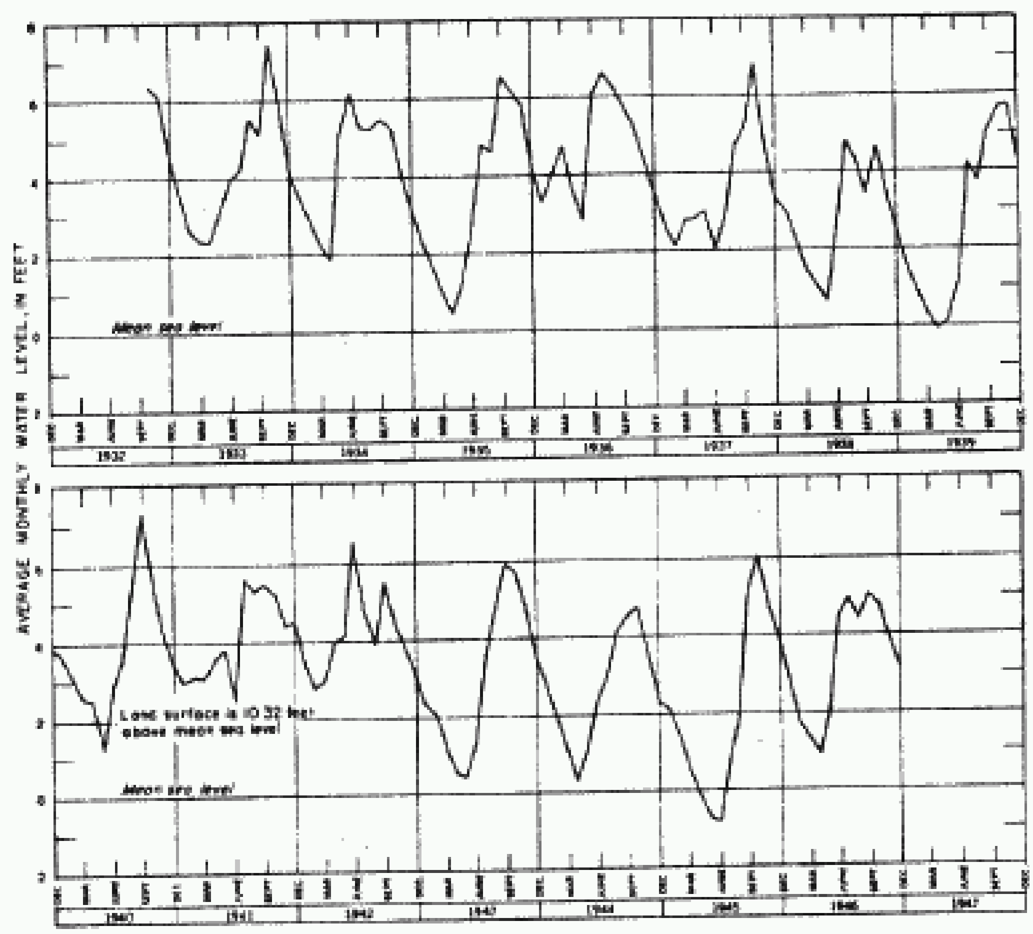


Figure 9. Water table fluctuations from 1932 through 1946 in an observation well near Florida City (from Parker and others, 1955).

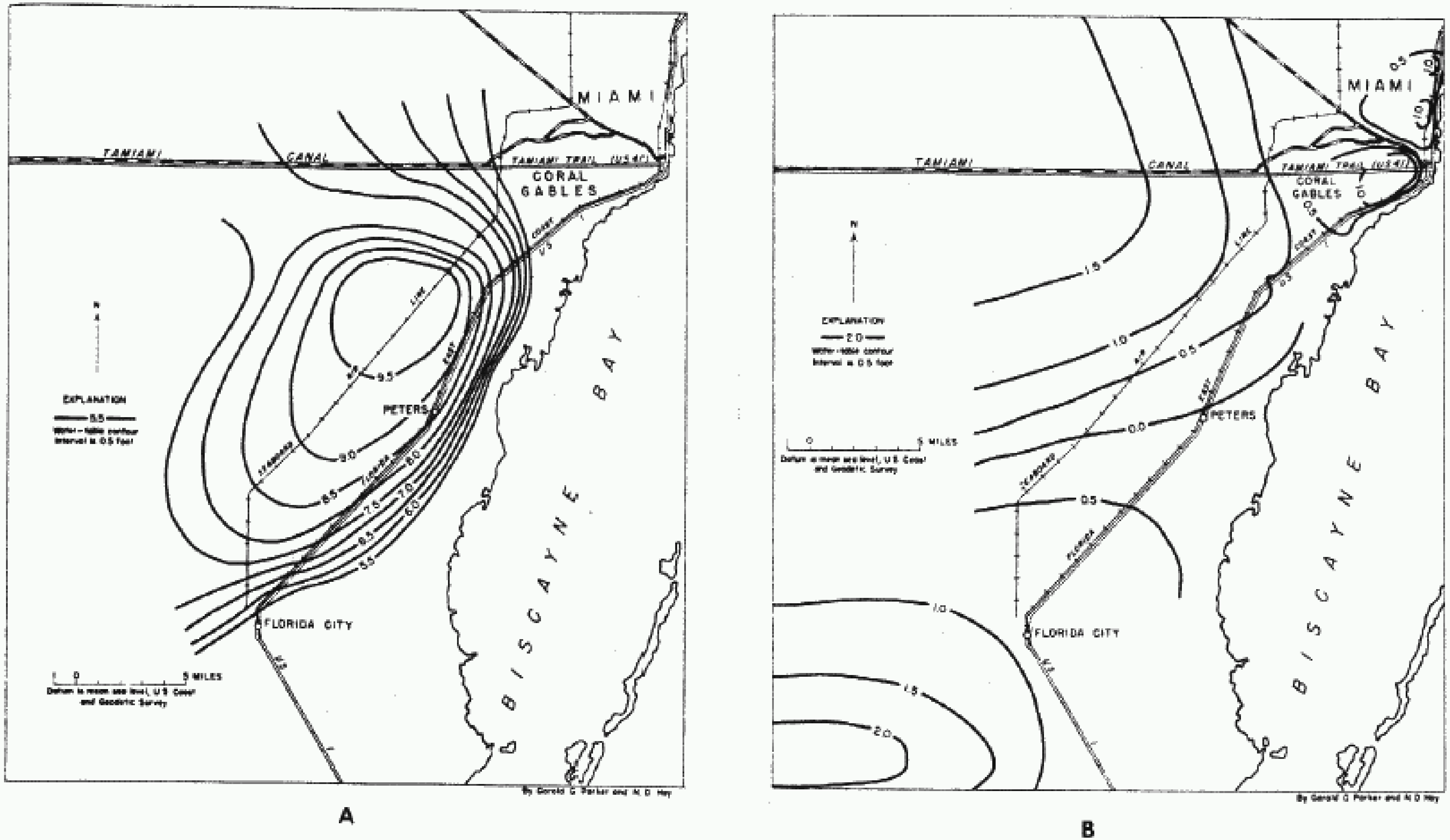


Figure 10. Water table maps showing change in stage between a high of September 30, 1940 (A) and a low point (B) of May 19, 1945 (from Parker and others, 1955).

level and water table level may only be surmised. Although relationships between water tables and sea level have been established for ideal, unconfined, island aquifers (Ghyben-Herzberg Relation; Todd, 1980), these do not allow us to predict, in other than a general way, the response of the Biscayne Aquifer to substantial sea-level lowering.

The Biscayne Aquifer is confined at its base by relatively impermeable Tertiary sediments at maximum depths of about 40 meters below the surface in the field study area. It seems possible that much of the portion of the Biscayne Aquifer lying within the Miami Limestone may have been drained during sea-level lowstands. Also, rainfall in south Florida is thought by some workers (Watts, 1975; Moran, 1975) to have been considerably less during global glacial periods. Compared with today, the vadose zone of the aquifer may have been greatly expanded at the expense of the phreatic zone by diminished rainfall and low sea-level during most of the Late Pleistocene.

The development of south Florida during the last 80 years has also affected the Biscayne Aquifer. Prior to dredging, large volumes of water were ponded west of the ooid shoal ridge, and ran over rapids in the Miami River (fig. 11), and through other glades to the sea. By 1913 four major drainage canals had been completed from Lake Okeechobee to the east coast at West Palm Beach, Hillsboro, Fort Lauderdale, and Miami (fig. 12). Continued dredging and drainage are estimated to have lowered the average water table level by at least 2 meters. Besides lowering the water table, drainage and pumping have affected the freshwater/saltwater interface along the eastern margin of the aquifer. The intrusion of salt water into the aquifer has been well documented by Parker and others (1955). The zone of mixing at this interface, documented by Kohout (1960), has also migrated westward into the aquifer. This is perhaps most strikingly documented by historical records which indicate drinking water for ships was collected from springs issuing from the floor of Biscayne Bay (fig. 13) and along Silver Bluff (fig. 14). These springs are now dry and only brackish water seeps into Biscayne Bay. These changes in the hydrology of the aquifer make it very difficult to apply present observations to the long-term diagenetic processes in the Miami Limestone. Nevertheless, an understanding of these hydrologic relationships places some limits on models of diagenetic processes in the past.

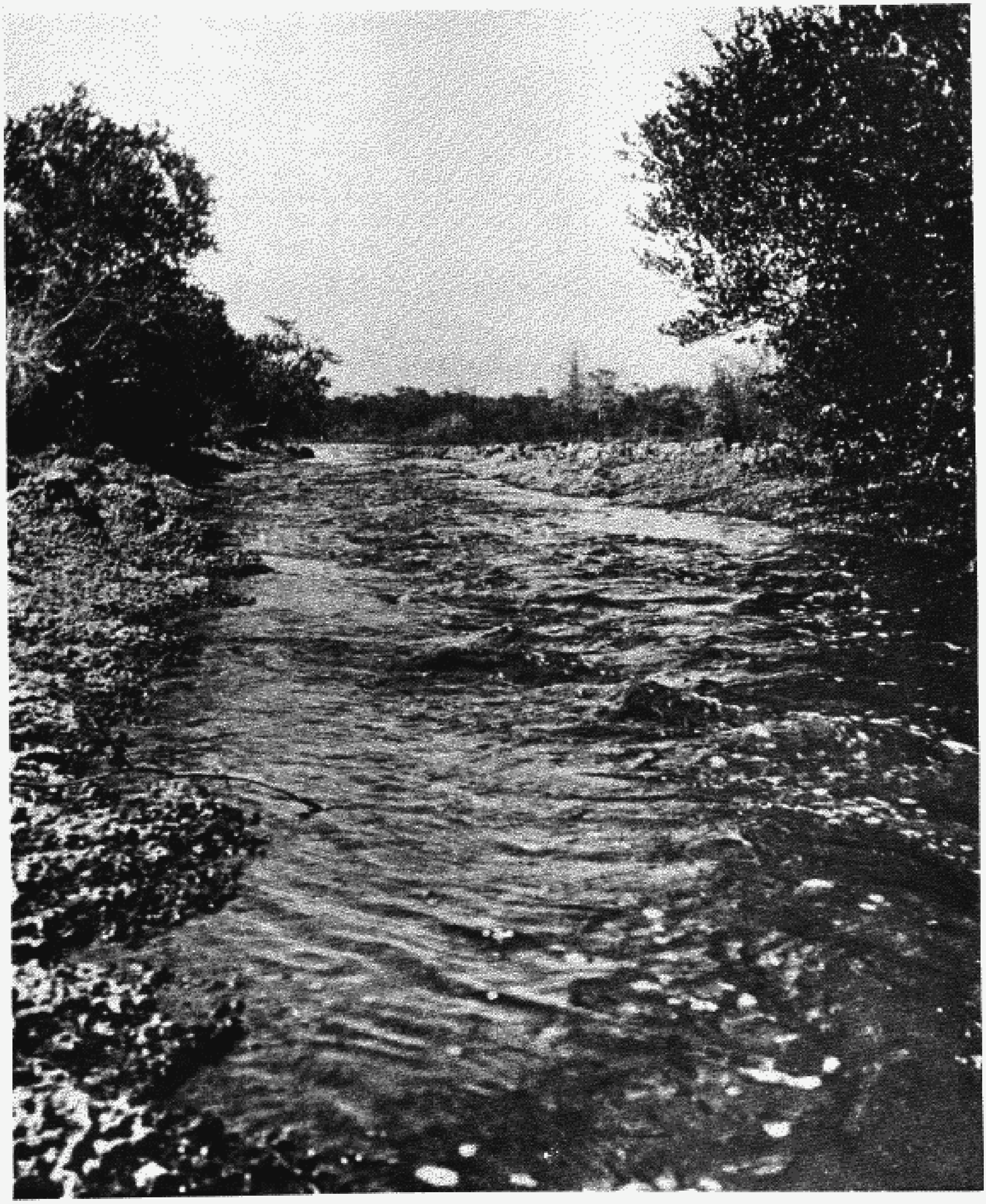
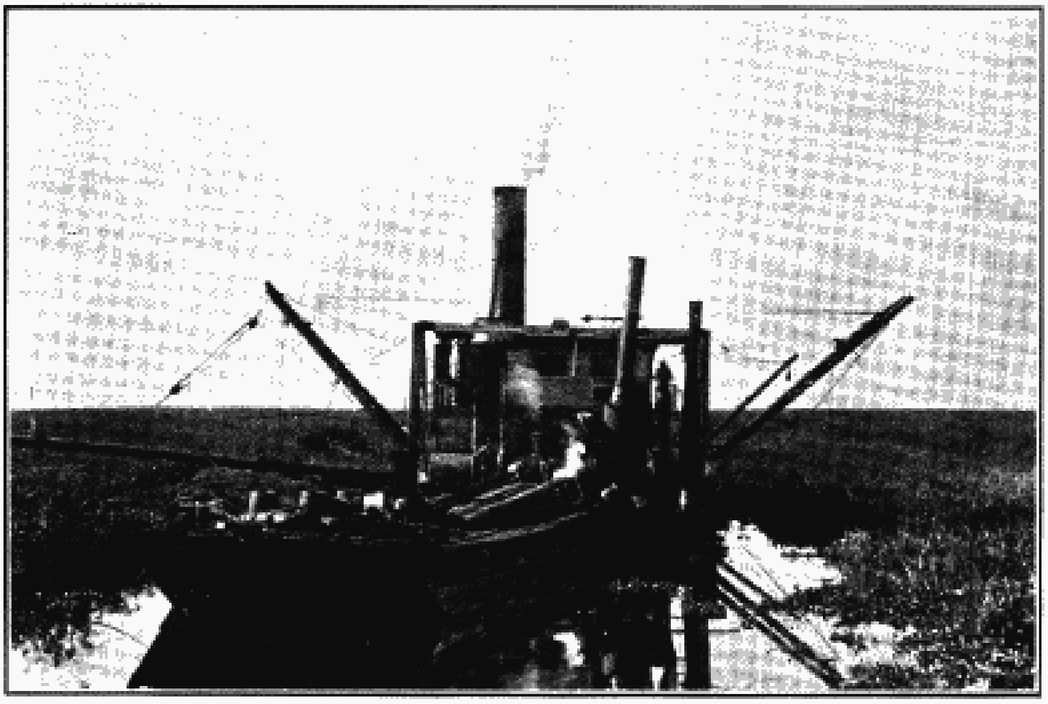


Figure 11. Rapids in the Miami River were vivid demonstration of the difference in water level on either side of the oolite ridge (Atlantic Coastal Ridge) prior to dredging. This photo was taken about 1895 near the present NW 27th Avenue bridge. (Courtesy of the Historical Association of Southern Florida.)



A DREDGE AT WORK IN THE EVERGLADES IN 1911.

This was in the North New River Canal 12 miles south of Lake Okeechobee. This area is now the center of a big sugar cane growing industry. The saw-grass of the Everglades, like a vast wheat field, stretches in all directions.

Figure 12.

Figure 13. Boatmen collect a cask of fresh water from spring in Biscayne Bay driven by the hydraulic head of high water in the Everglades. Note the tree line in the background Photograph by Ralph M. Monroe taken between 1883 and 1900. (Courtesy of the Historical Association of Southern Florida).

Figure 14. A portion of Silver Bluff with a spring known as the "Devil's Punchbowl" below the arched hollow on the right. A man takes a refreshing drink while being photographed by Ralph Monroe between 1883 and 1887. All such springs along Silver Bluff are now dry or brackish due to lowering of the fresh water table and intrusion of salt water along the coast. (Courtesy of the Historical Association of Southern Florida).

FIELD STOPS

All but one of the five field stops that follow are on the barrier bar (STOP locations on inside front cover). One stop, STOP IV, is west of the ooid shoal complex. These stops are selected to provide a broad spectrum of features characteristic of the Miami Limestone. They are chosen to exhibit the following Pleistocene features:

STOP I: Active Ooid Sand Shoal
STOP II: Sea Cliff Exposing Channelled Bar
STOP III: Seaward Stabilized Sand Flat
STOP IV: Platform Interior Sands and Base of the Miami Limestone
STOP V: Islands on the Shoals

Other stops which are referred to in the text or illustrations are listed with brief descriptions in Appendix II.

While the stops chosen for this trip exhibit a wide variety of the characteristic features of the Miami Limestone, it is important to realize the bias in our sample set, in this case the localities visited. Outcrops in the Miami area are restricted to the areas of highest relief, in effect confined to the seaward barrier bar. The barrier bar is only a small portion of the whole of the Miami Limestone. Thus, participants in the trip are cautioned against the impression that the predominant feature or facies of the Miami Limestone is bedded. Evans (1982) has demonstrated that the Coastal Ridge is less than 40% bedded rock, and that the burrowed facies, which we see relatively little of, predominates, comprising over 60% of the section on the Atlantic Coastal Ridge. It should also be considered that Hoffmeister and others (1967) have indicated an areal extent for the bryozoan facies of over 5,000 km^2 (2,000 mi^2) making it clearly the most important facies of the Miami Limestone by volume.

STOP I: ACTIVE OOID SAND SHOAL
(Coral Gables Waterway and LeJeune Avenue)

Beneath the LeJeune Ave. bridge are exposures of cross-bedded oolite which record several episodes of higher energy ooid sand deposition and related lower energy periods characterized by bioturbation. This locality lies within the barrier bar (figs. 5 and inside front cover), about 150 meters west from the eastern, seaward edge and about 10 km from its northern terminus. The waterway cut reveals ooid sands which moved in southeast, east, and northeast directions. These sands were not deposited continuously, but rather are naturally divided into discrete depositional units by reference to loci of bioturbation or shell layers. Generally, the more bioturbation, the more disrupted the stratigraphy, and the longer that surface existed in a low-energy regime. These depositional breaks occur during varying lengths of time and may be recognized as different types of surfaces which form the boundaries of cross bed sets. Following the terminology of Kocurek (1981) and Brookfield (1977), these surfaces here are termed first-, second-, and third-order bounding surfaces.

Boundary Surfaces and other Sedimentary Structures

Bounding surfaces represent periods of erosion, nondeposition or slow deposition ranging from minutes to tens or even hundreds of years. They form for a great variety of reasons and scrutiny of the physical characteristics of bounding surfaces often provides clues to their origin and duration.

First-order Bounding Surfaces

At least three examples of first-order bounding surfaces are visible at this stop. These surfaces are divisible into two categories: burrowed surfaces, and surfaces which separate two distinct sets of crossbeds by a major erosional event. Burrowed first-order bounding surfaces delineate the units of accumulation described by Evans (1982), whereas first-order surfaces which are not burrowed separate grouping of crossbeds.

The oldest first-order bounding surface in this section separates burrowed, pelloidal-ooid grainstone from bedded oolite grainstone (fig. 15). This surface is marked by a thin (2 cm) micritic layer between the burrowed and bedded facies. The mud layer is not mixed into the underlying pelloidal grainstone, although a few burrows extend through it, indicating relatively rapid burial by oolitic sand waves after its deposition. Rapid burial by sand waves prohibited the incorporation of this mud layer into the underlying sediments by bioturbation. The significance of this mud layer is twofold: 1) a significant break in sedimentation occurred between the burrowed pelloid-ooid grainstone and the mud layer, and 2) the time value of this first-order bounding surface is of large enough magnitude to allow the infestation of the surface of the pelloid-ooid grainstone by a burrowing fauna, and for this fauna to obliterate all primary physical structures in this rock by syndepositional burrowing.

Perkins (1977) considered this surface to be a subaerial exposure horizon; however, we see no compelling evidence for subaerial exposure along this surface. This contact represents the reactivation of a stabilized burrowed surface, first by a storm deposit (evidenced by the micrite layer), followed by burial under active ooid sand waves.

A later first-order bounding surface is exposed about 1 meter above the water level (fig. 16). This surface is not as pronounced as the lower surface described above, but shows evidence of the early stages of colonization by burrowing organisms. The burrows extend downward from the surface no more than about 20 cm and burrowing was not intense enough to obliterate all primary physical structures. The time of nondeposition represented by this surface is obviously considerably less than that represented by the lowermost surface, reactivation of the surface coming before the burrowing fauna was well established.

The youngest first-order boundary surface is exposed about 3 meters above sea level (fig. 16). This surface is a very coarse-grained, well cemented horizon separating several sets of crossbeds. Immediately above it lies a thin horizontal layer of coarse shell grains and other debris left after a period of winnowing, perhaps by storm-generated currents. Components of the lag deposit are Donax sp.

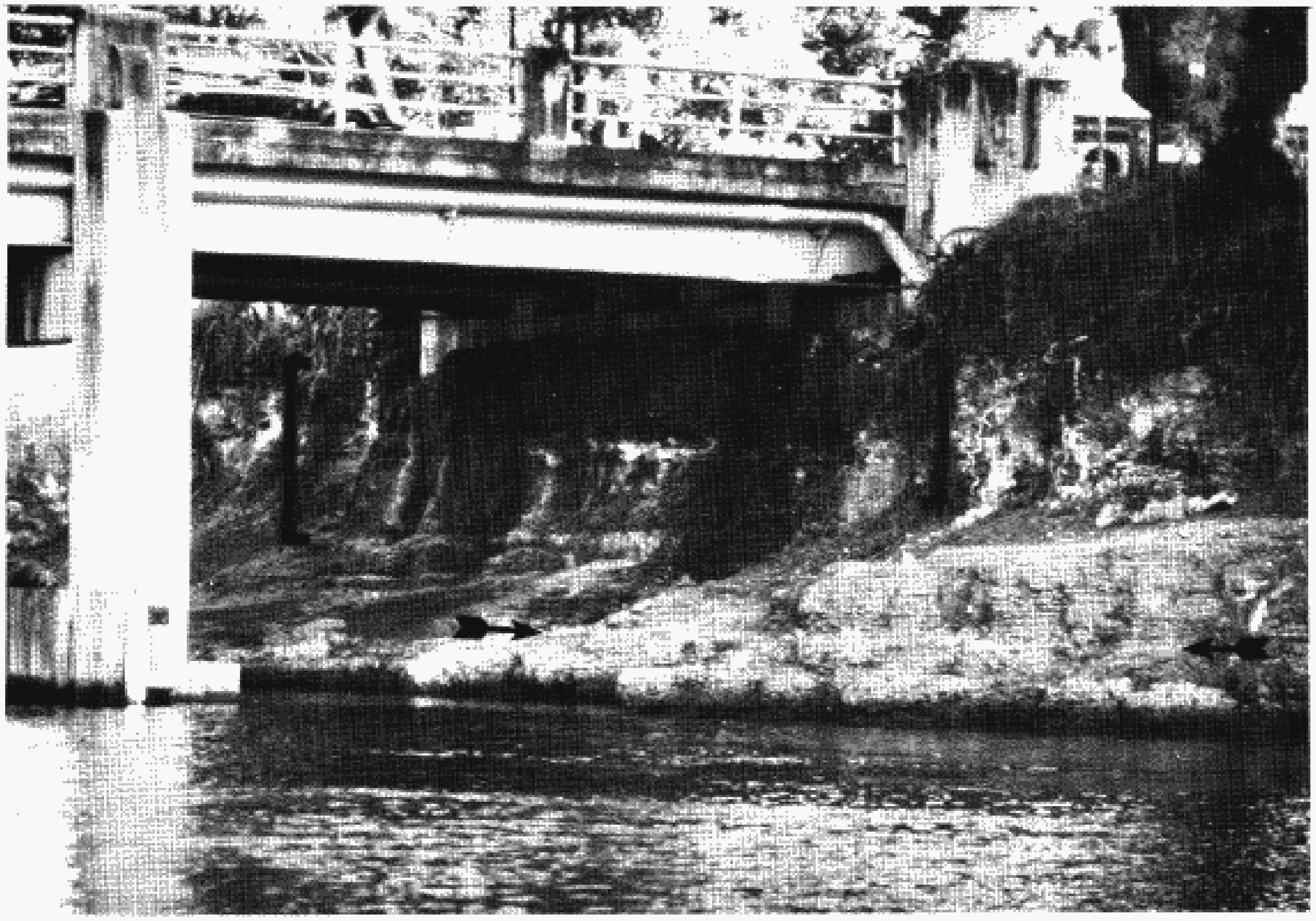


Figure 15. STOP I. Outcrop at Coral Gables Waterway and LeJeune Avenue. Arrows point to mud layer at first-order bounding surface separating low-energy burrow-mottled grainstone from overlying, high-energy crossbedded oolite. Interval shown in Figure 16 in brackets.

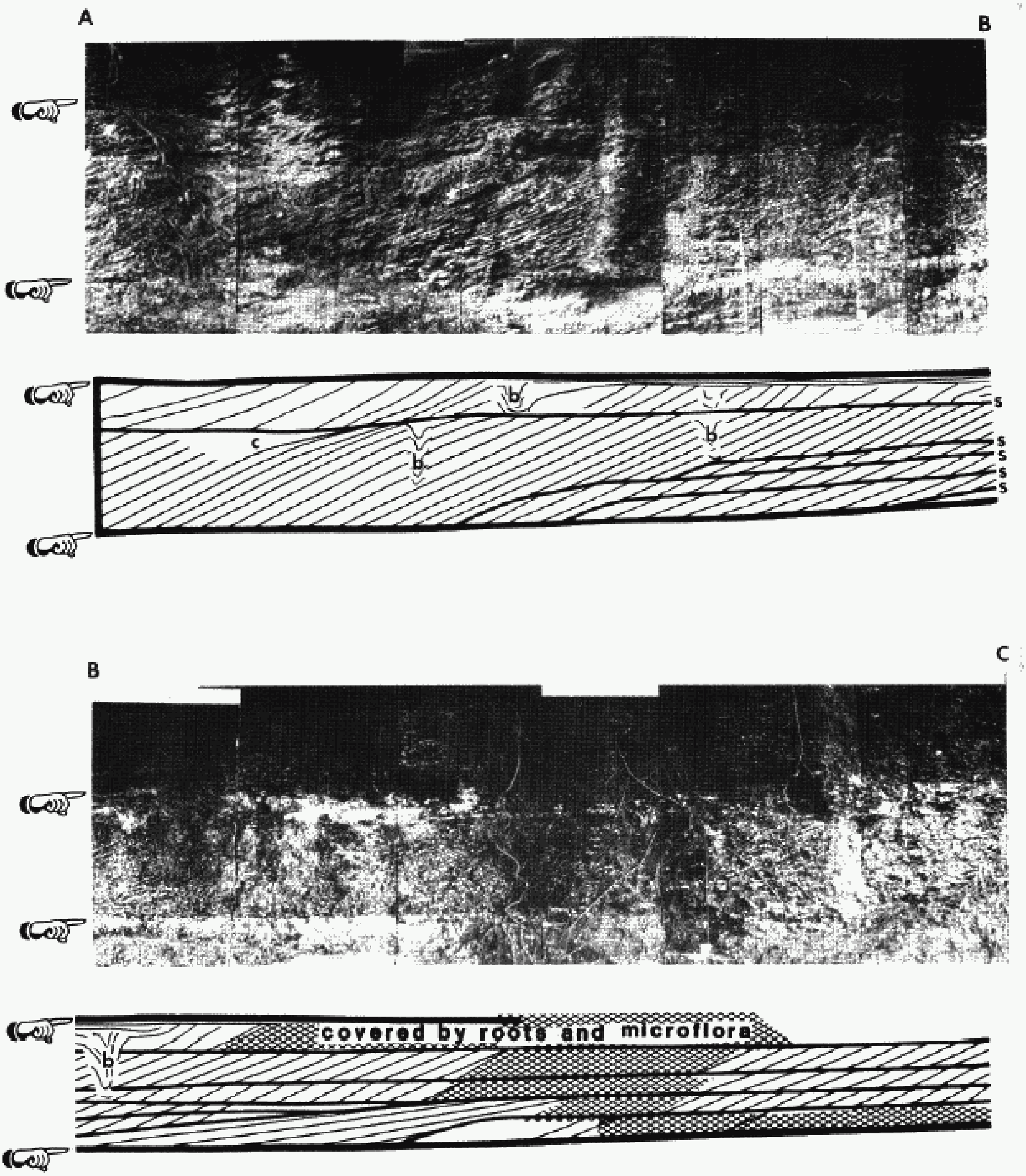


Figure 16. The portion of the outcrop in brackets from Figure 15 at STOP I. Construction of the waterway began in 1925 and continued inland until 1942. First-order bounding surfaces are pointed out at prominent coarse lag deposits and burrowed horizons. Second-order bounding surfaces (s), nested-cone burrows (b) and convex-upward cross sets (c) are illustrated on the line drawings of the outcrop. Tape measure visible in several photos is one meter.

and other molluscs, bryozoan fragments and very coarse ooids. The lag may represent a single, unusually large storm or a series of smaller disturbances which combined to produce this 5-cm-thick rubble zone. Several nested-cone burrows lie at or near the upper first-order boundary surface (fig. 16). These are escape structures left by the burrowing anemone Phyllactis conguilegia (Shinn, 1968) an organism which is able to tolerate high-energy environments. Between this bounding surface and the one at the mud layer about 3 meters below lie eight to ten sets of cross bedded oolite. These sets probably record the migration of a train of sand waves over a stabilized, burrowed, ooid sand surface. Each sand wave left behind a portion of its bulk in the form of a thin set (up to 1 m) of cross strata. Trains of sand waves migrating across such surfaces can be seen today in the Bahamas. The time value of this bounding surface is unknown. It is clear, however, that unlike the lower two first-order bounding surfaces exposed in this section, conditions here were not quiet or stable enough to allow infestation of the surface by a burrowing fauna. Relatively strong currents prevailed at this surface with resultant bottom scour, as indicated by the coarse skeletal lag which accumulated here.

Typical first-order bounding surfaces and associated features are illustrated in Figures 17-22. Several beautifully preserved nested-cone burrows are shown in Figure 23. An experimentally produced burrow of a burrowing anemone is shown for comparison in Figure 24 (from Shinn, 1968).

Second-order Bounding Surfaces

Second-order bounding surfaces define the individual sets of oolite cross-beds between the first-order surfaces shown here. The sets vary between about 5 cm and 1 meter thick. Many sets are tabular for many meters along the length of the outcrop, that is, they are defined by nearly parallel second-order bounding surfaces (figs. 16 and 23d). Some sets, however, are seen to wedge over varying distances along the outcrop. Tabular sets represent migration of relatively straight-crested sand waves through the area of this stop. Wedge-shaped sets can result from more sinuous, possibly lobate, dune-like forms which migrate in more lobate forms and interfere with each other's progress. For example, it is not uncommon to see one of two adjacent sets overtake another resulting in one set abruptly terminating and being replaced by another along the direction of transport. Excellent examples of this process may be seen in the crossbeds below the bridge about 2 meters above sea level (fig. 16). Burrows rarely originate on second-order boundary surfaces but frequently pass through them (figs. 23a and d). Second-order bounding surfaces are the surfaces across which sand waves migrate within a train of migrating sand waves, often truncating the underlying cross beds. Thus, they also represent episodes of no deposition or erosion, but not nearly as extensive as well burrowed or deeply eroded first-order surfaces.

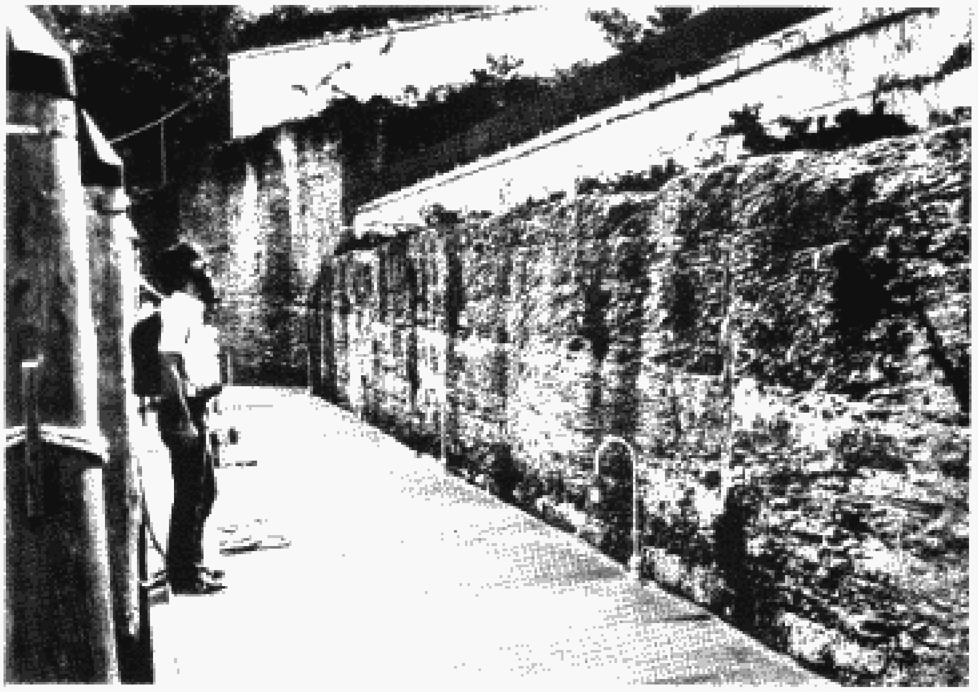


Figure 17. Parallel first-order bounding surface (arrows) separating wedged and undulating second-order bounding surfaces. Locality is along private boat dock about 100m east of STOP I.

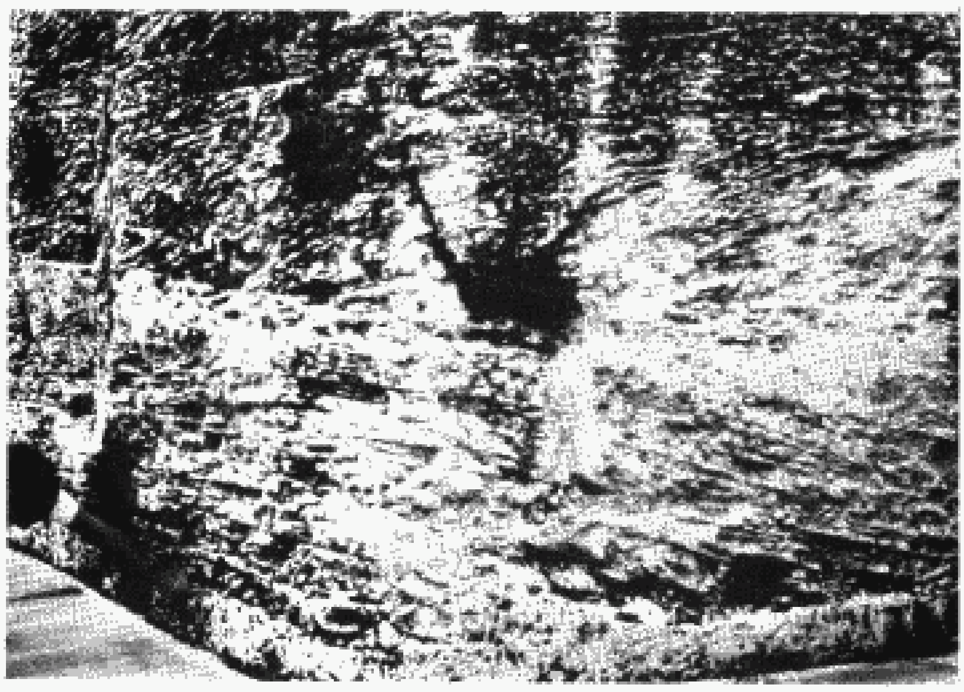


Figure 18. Three dimensional view of cross sets shown in Figure 17 exposed at corner of excavation. Person points to first-order bounding surface overlain by crossbedded oolite dipping into plane of photograph.

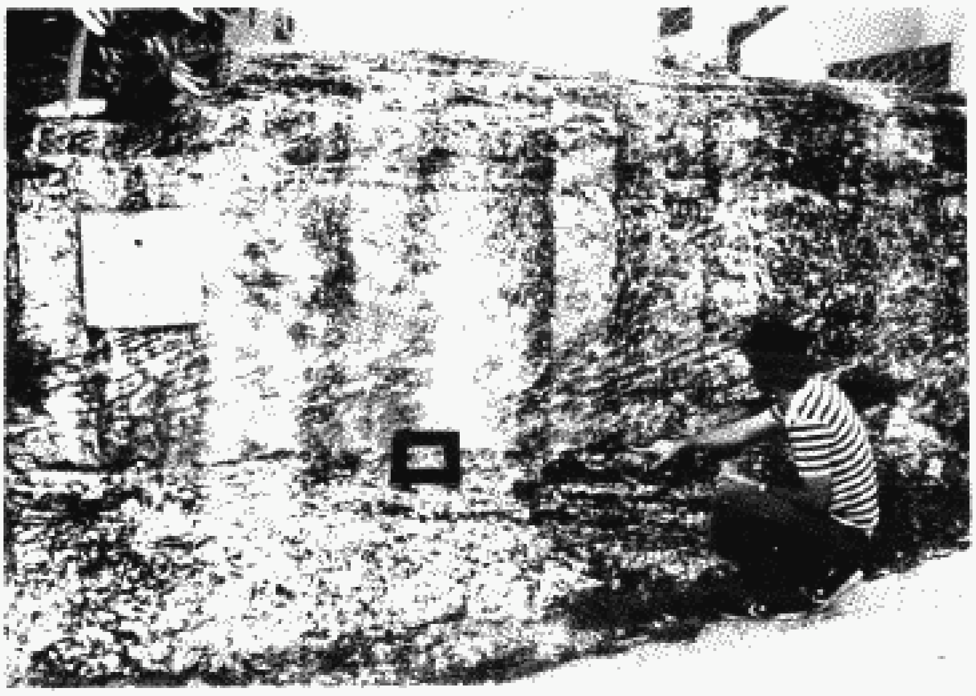


Figure 19. First-order bounding surface at additional Stop 5. Box indicates portion of lag deposit illustrated in Figure 20.

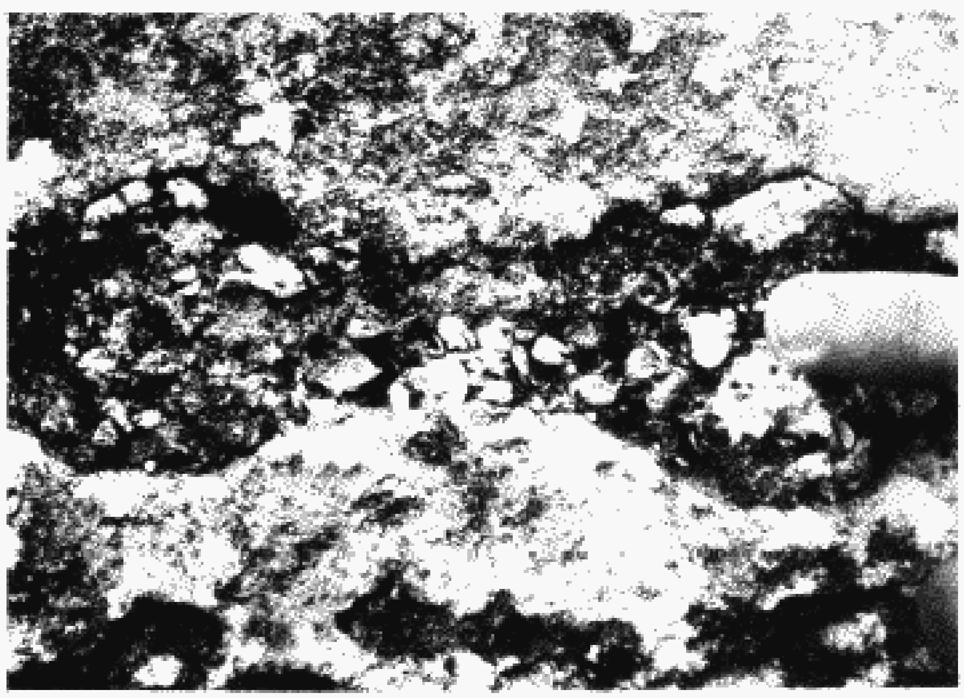


Figure 20. Coarse lag deposit of Donax sp. shells and large ooid grains at first-order bounding surface, additional Stop 5.

Figure 21. First-order bounding surface overlain by crossbedded oolite which in turn is overlain by laminated oolitic grainstone, a portion of which is shown in detail in Figure 22. Exposure is about 1.5m high.

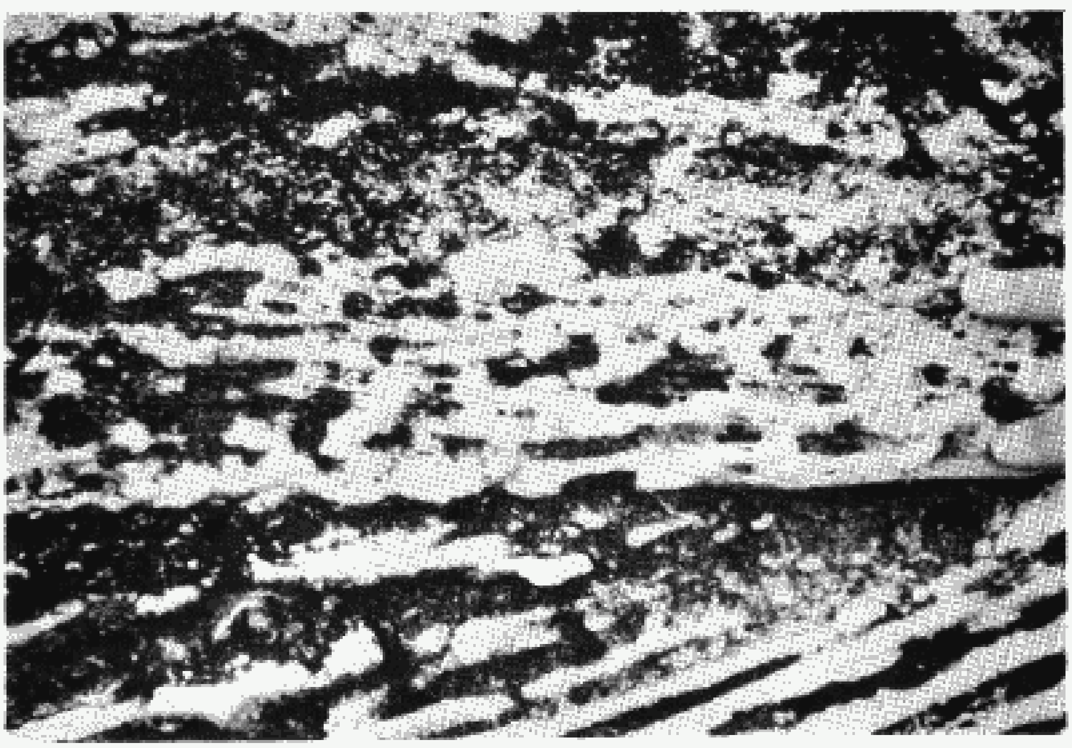


Figure 22. Detail from Figure 21 showing irregular, patchy cementation which partially obscures primary laminations in oolitic grainstone. Additional Stop 6.

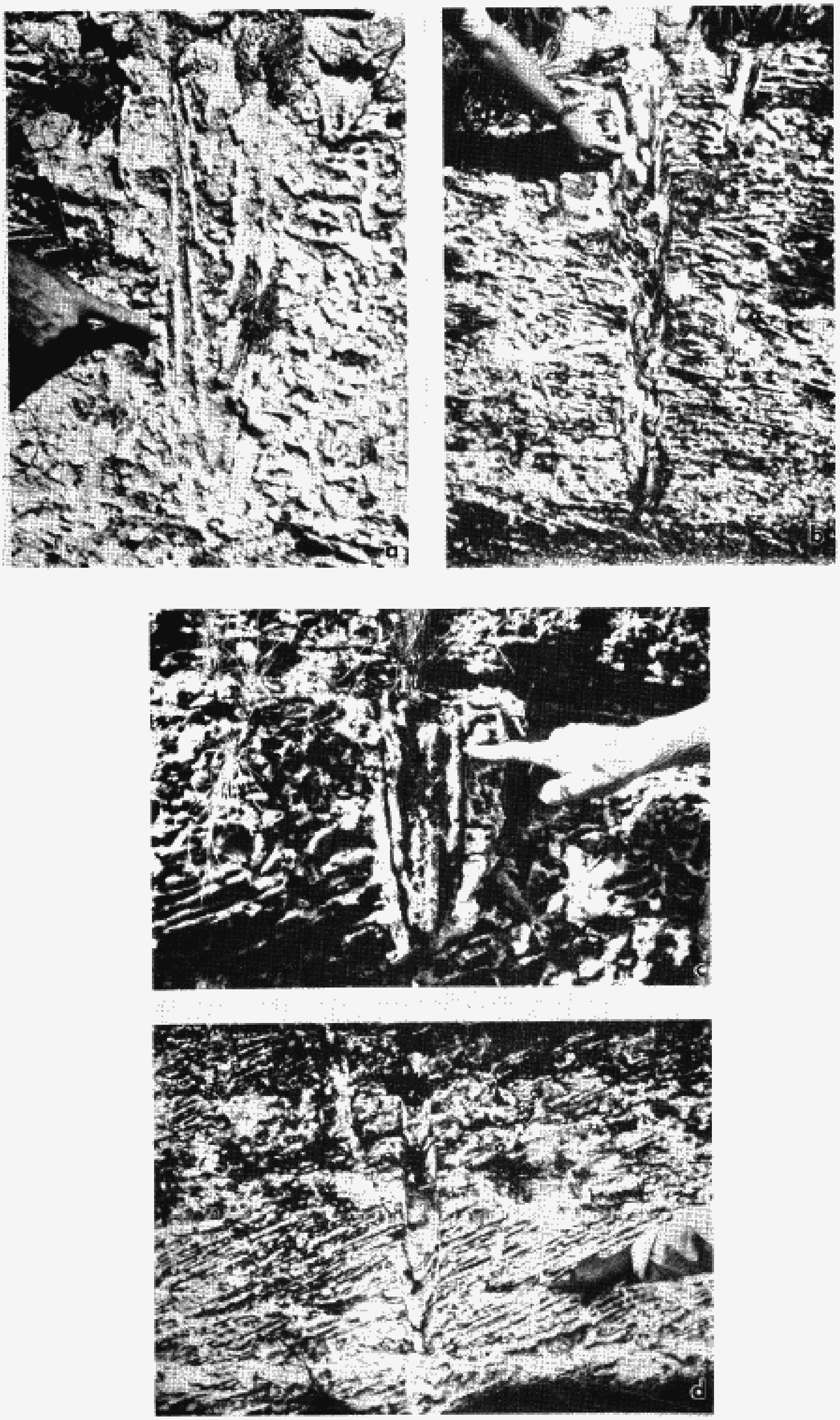


Figure 23. Nested-cone burrows. a-c from additional Stop 12, d is from additional Stop 9. Note burrows crosscut second-order bounding surfaces in b and d.

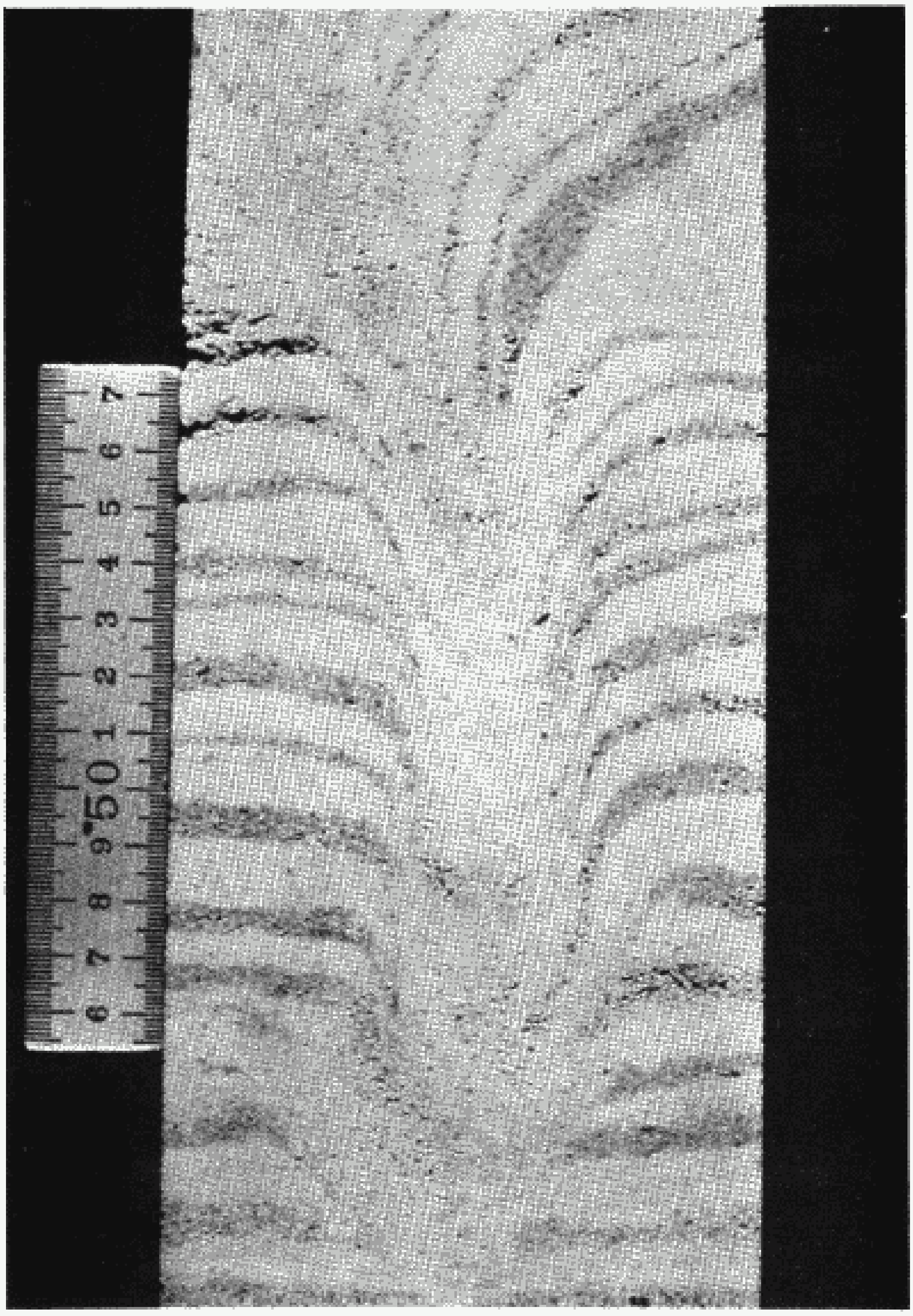


Figure 24. Experimentally produced nested-cone burrow. Burrowing anemone was buried in alternating layers of ooid and algal sand. After the creature had burrowed its way to the surface, the sand was impregnated with plastic resin and slabbed to reveal burrow.

Third-order Bounding Surfaces

Third-order bounding surfaces are subtle features which in the Miami Limestone are most commonly seen as reactivation surfaces. These features record breaks in the otherwise continuous deposition of a cross set. They are recognized by an erosion surface along the cross strata, sometimes a burrowed horizon or a change in dip angle of the cross beds. Two reactivation surfaces are illustrated in Figures 25 and 26.

More Interpretations

The boundaries between individual foresets define the direction of movement of the bed form and are the shortest record of temporal variation in sedimentation rates evident in this outcrop. The sets are the lower portions of slipfaces which may have been much higher and were truncated prior to the deposition of overlying strata. Individual sets greater than two meters have been exposed in excavations along Brickell Avenue.

Crossbeds form from variations in grain size, sorting, and packing. Average dip angle here is about 26° and although dip direction generally contains an eastward component, it varies from N. 70° E. to S. 60° E. Many of these cross sets were formed by avalanching of sand down slipfaces on the lee side of sand waves. The angle of repose of modern ooid sand from Cat Cay shoals based on flume experiments is 27° on average (Christopher Schenk, personal commun., Dec., 1982). Not all cross sets, however, are the result of avalanche processes. One conspicuous set, 2 meters east of the bridge and 1 1/2 meters above sea level, displays convex upward cross-beds, suggestive of a bulge or small spillover lobe on the leeward side of a sand wave (fig. 16) which formed after the coalescing of several small sand waves to produce one larger bedform.

It is important to stress that although crossbeds and the bounding surfaces have readily recognized modern counterparts, long-term studies designed to demonstrate rates of accumulation and modes of preservation of these features have not been made.

The burrowed facies exposed here just above sea level is interpreted by Evans (1982) to be the top of a sediment package, termed a unit of accumulation. A package starts at a sharp contact of crossbedded oolite overlying burrowed grainstone and grades upward into increasingly burrowed sediment. First-order bounding surfaces such as the one at the base of this package are common in the cross bedded facies of the Miami Limestone. First-order bounding surfaces with burrowed facies overlying cross bedded sands are rare (fig. 27). A possible modern analog of a package boundary (bedded facies overlying burrowed facies) is illustrated in Figures 28 and 29 (location A).

The diverse cross bed directions observed at this outcrop, although generally eastward, are difficult to explain by any model involving consistent transport directions. Rather, they indicate a variety of movement directions for individual bedforms or portions of bedforms. Such complexities of ooid sand movement are more easily envisioned by reference to Figure 29. This aerial photograph of the seaward portion

Figure 25. Third-order bounding surface (reactivation surface) exposed along the outcrops of additional Stop 12. Note how cross strata terminate against the surface indicated by arrows.

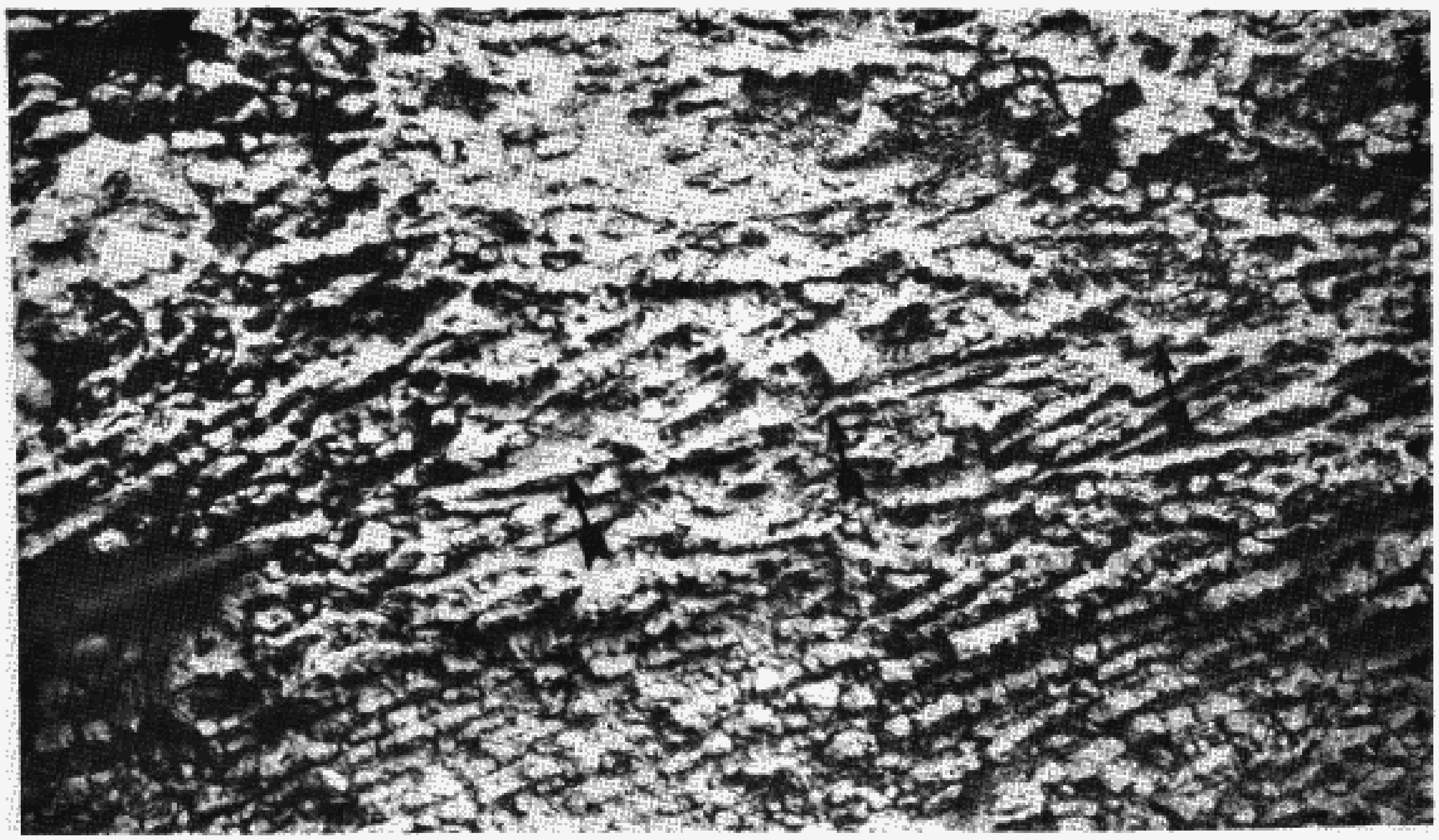


Figure 26. Third-order bounding surface exposed at additional Stop 9. Reactivation surface is indicated by arrows.

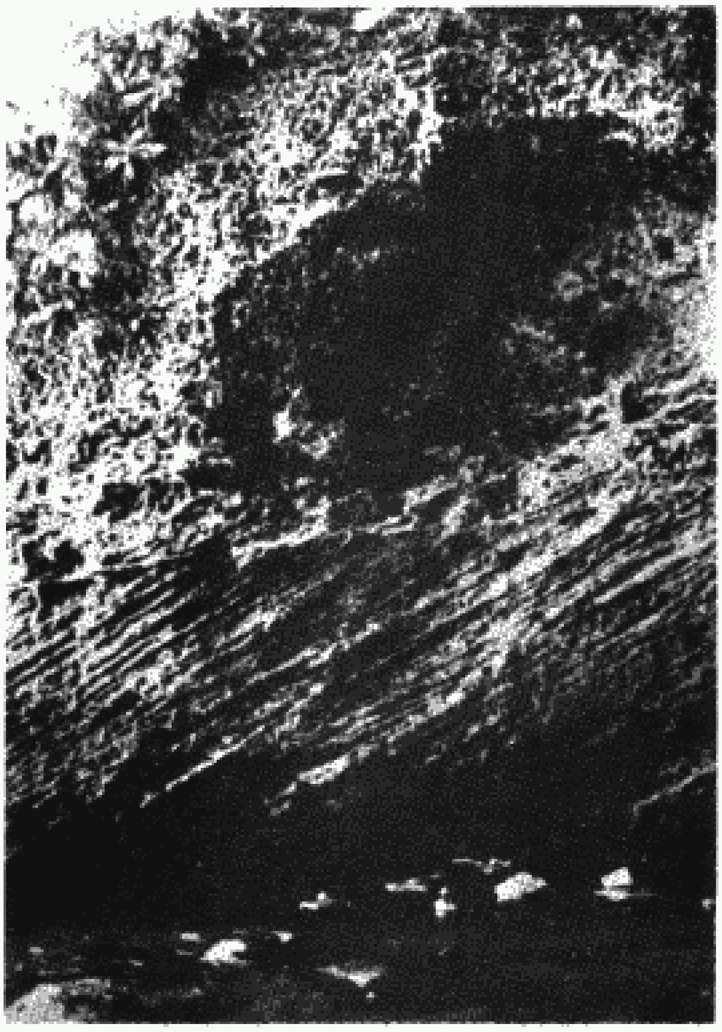


Figure 27. Burrow-mottled oolitic grainstone overlying and in sharp contact with crossbedded oolite. Such first-order bounding surfaces are very rare in the Miami Limestone. This outcrop is about 2m high and has a well developed sea-level notch at its base. It is located at additional Stop 11.

Figure 28. Crossbedded ooid sand waves migrating over stabilized, burrow-mottled sand near Joulters Cays, Bahamas. Process illustrated by this figure is similar to that which produced contacts of bedded oolite on burrowed grainstone illustrated in Figures 15, 18 and 19.

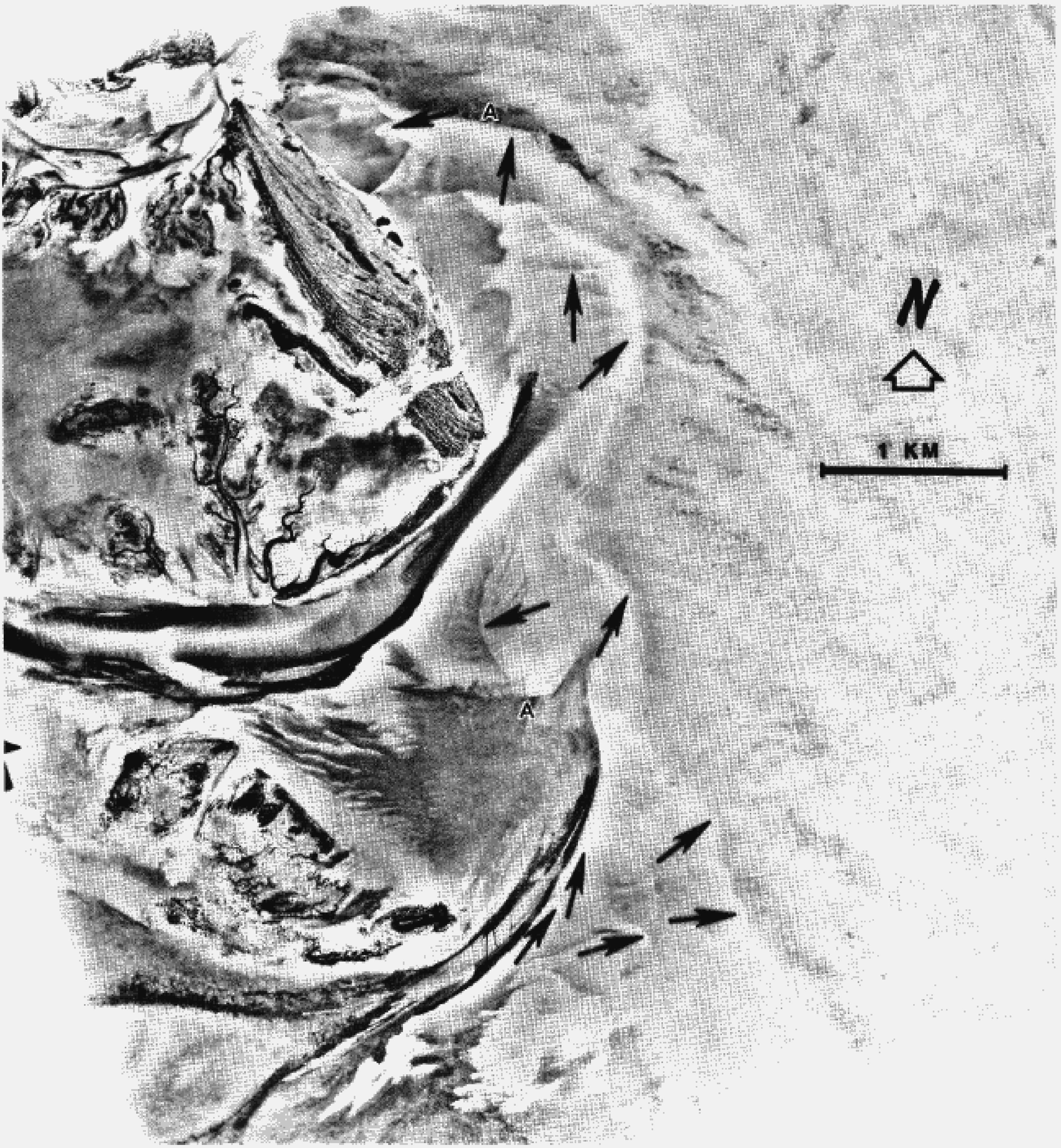


Figure 29. Aerial photograph of a portion of the Joulters Cay area, Bahamas. Arrows indicate the diversity of sand movement directions formed in areas which are dominated by ebb or flood currents. An area where bedded sands are covering stabilized, burrowed sediments, like that illustrated in Figure 28, is located by A.

of a modern ooid shoal complex north of Andros Island, Bahamas, illustrates the diversity of sand movement in such hydrologically complex areas.

The diversity of crossbed directions observed at this outcrop provides valuable information on the origin of the barrier bar. It is apparent that this portion of the barrier bar was not deposited by the simple spit accretion model suggested by the topography in the Black Creek area described by Halley and others (1977). It is perhaps more appropriate to view at least this portion of the barrier bar as having its origin in coalescing tidal deltas and sand waves, much as the situation depicted in Figure 29 illustrating multiple crossbedding directions. The general eastward directional component of dip directions here suggests the sand bodies were dominated by ebb flow from the bank (Hine, 1977).

Diagenesis

After examination of the beautifully preserved foresets and burrows at this locality, the question arises as to why such sedimentary structures should be so well preserved. A few minutes of looking will convince you that these features are preserved and actually enhanced by selective cementation. In foresets, for example, alternate layers are well cemented and poorly cemented, on an average thickness of about 2 cm per couplet. Well cemented layers weather resistantly to enhance the visibility of primary sedimentary structures. This thickness and style of preservation are typical of Miami Limestone cross sets regardless of elevation relative to sea level or dip angle, although thinner cross set layers are known. The mechanism for this selective cementation is one of the most fascinating problems of the Miami Limestone.

Several pertinent observations regarding selective cementation may be made at this outcrop:

1. Most frequently, it appears that finer grained layers are preferentially cemented;
2. Often, however, coarse-grained, skeletal-rich horizons are also well cemented, for example the coarse lags at first-order bounding surfaces;
3. Although one is struck by the continuity of these well cemented layers, many are quite discontinuous in detail, consisting of discrete, aligned, well cemented patches a few centimeters in lateral extent and elongate in the dip direction (figs. 21 and 23d);
4. Areas can be found in which alternating cross beds are equal in grain size and sorting, but layers with more compact grain packing are selectively better cemented;
5. Cement mineralogy is low-magnesium calcite, usually subhedral or blocky in texture, typical of early, fresh water cements in Pleistocene limestones (Friedman, 1964; Land, 1967);
6. At this locality well cemented layers contain primary, aragonitic ooids, some calcite replaced ooids and cement filling almost all pore space (fig. 30);

7. Poorly cemented layers contain little cement and substantial volumes of secondary (oomoldic) pore space. Where early cement morphology is preserved, the cement appears to be dominantly of phreatic style in the sense of Halley and Harris (1979) (fig. 31).

Observations 1 and 4 suggest that larger specific surface area may be a strong control on this selective cementation. Such control may be affected by more nucleation sites, lower permeability, or higher specific retention of finer grained or tighter packed layers. An explanation, which originated from the Shell Oil Research Co. office in Coral Gables (1954-1968), explained that this selective cementation resulted during precipitation in fresh water held by capillarity in finer grained layers during the long history of these sediments in the vadose zone. This is not easily reconciled with the observed cement morphology of the poorly cemented layers. Perhaps the phreatic-style cements were developed during very early subaerial exposure of the Miami Limestone, while the shoal was an island only a few feet above sea level and contained a small freshwater aquifer. Subsequent vadose cementation may then have resulted in continued dissolution in coarse-grained layers and cementation in fine-grained layers. This seems unlikely, however, because vadose cements are not seen to overlie phreatic cements as described from Bermuda by Schroeder (1973).

Perhaps these cements represent the product of ancient fluctuating water tables related not only to sea-level fluctuations but also to seasonal rain storm and tidal variations typical of the aquifer today. It is the opinion of one of us (RBH) that controls governing dissolution and reprecipitation are not well understood on the scale of this selective cementation, and it may be possible for water of different saturations with respect to calcite to exist in close proximity for short periods of time. Observations 6 and 7 suggest a net transfer of material ($CaCO_3$) from coarse-grained to fine-grained layers. This process may be possible in the phreatic zone by rapid flow of water undersaturated with respect to aragonite along coarse-grained layers to some depth below the water table. Subsequent calcite precipitation may then be localized by nucleation sites or surface properties largely within fine-grained layers.

Whatever the mechanism of this selective cementation, it is not restricted to the cross bedded facies of the Miami Limestone. Examination of the burrowed facies near sea level reveals the same style of early diagenesis. Among the myriad of burrows at this level are some well defined Callianassa sp. burrows characterized by a diameter of 1 to 3 cm, mud-lined wall, and bumpy exterior of the mud lining (fig. 32). The interiors of these burrows are characterized by vuggy porosity while the walls are well cemented. Shinn (1968) described the typical filling of these burrows as storm-generated traction deposits, usually coarser than the surrounding sediments (figs. 32b and 33a) which produced textural and permeability differences leading to later preferential diagenetic pathways in the burrows. In our case, these permeability differences have led to lithification of the fine-grained burrow wall and dissolution of the infilling sediment of many types of burrows. This is observed commonly throughout the Miami Limestone (fig. 33b).

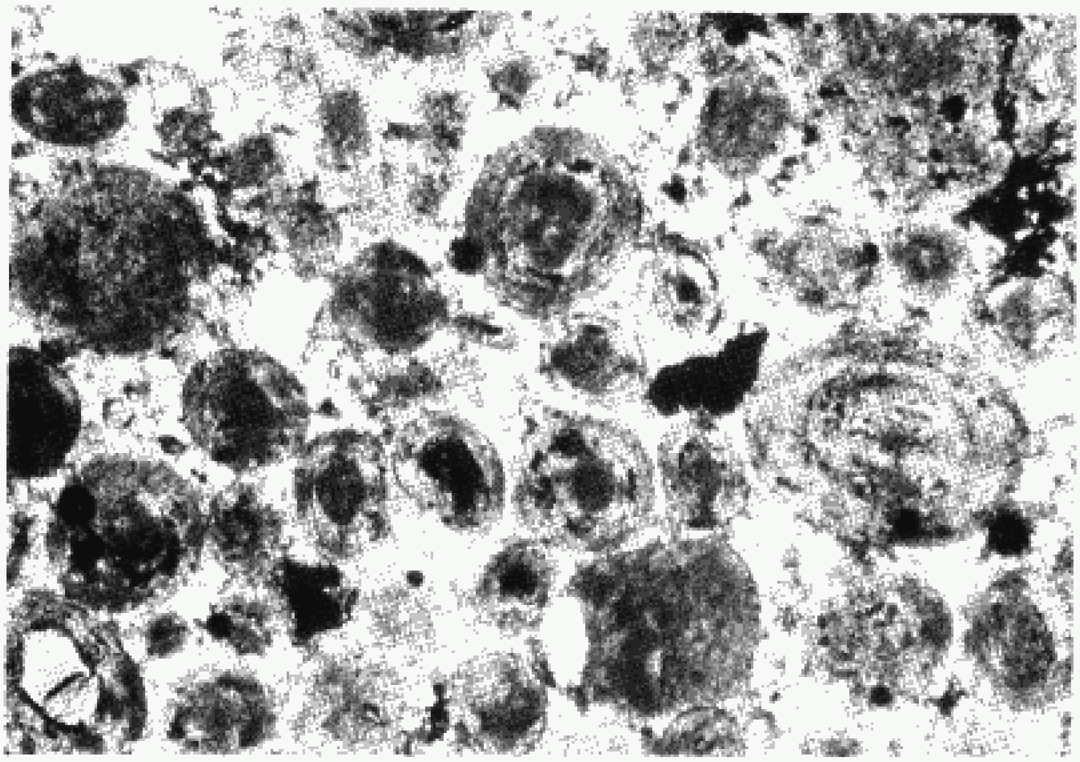


Figure 30. Photomicrograph of well cemented layer of bedded oolite. Width of photo is 3.5mm.

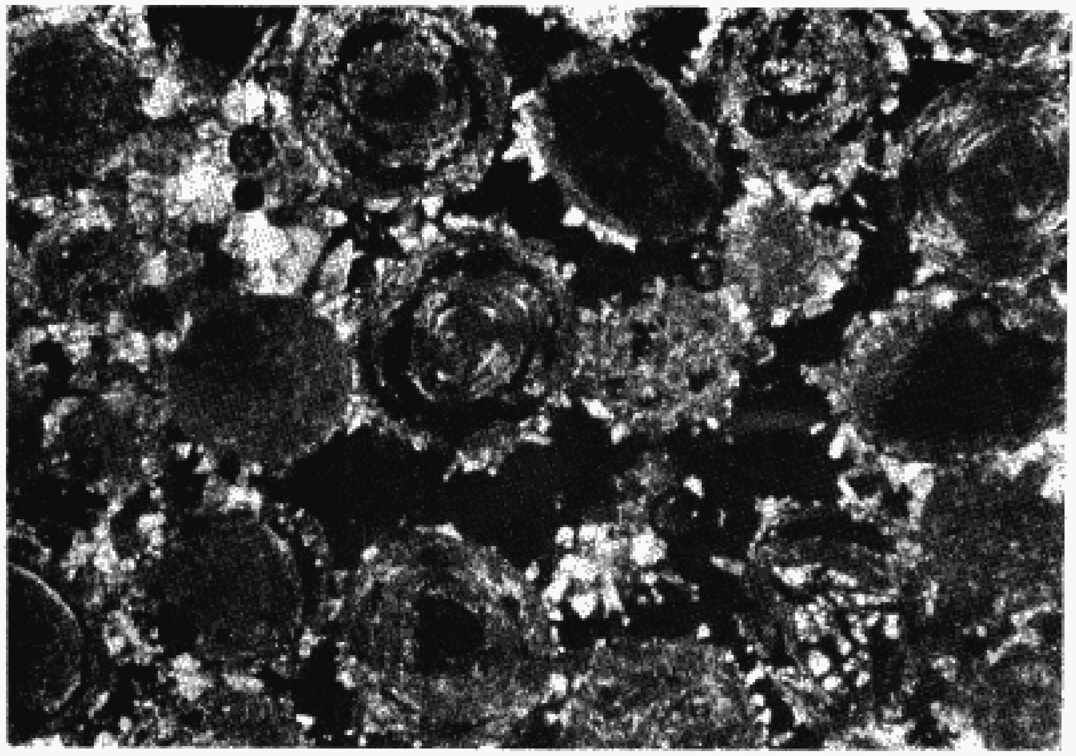


Figure 31. Photomicrograph of poorly cemented oolite layer illustrating excellent primary and secondary pore space (black) and phreatic-style calcite cement. Width of photo is 3.5mm.

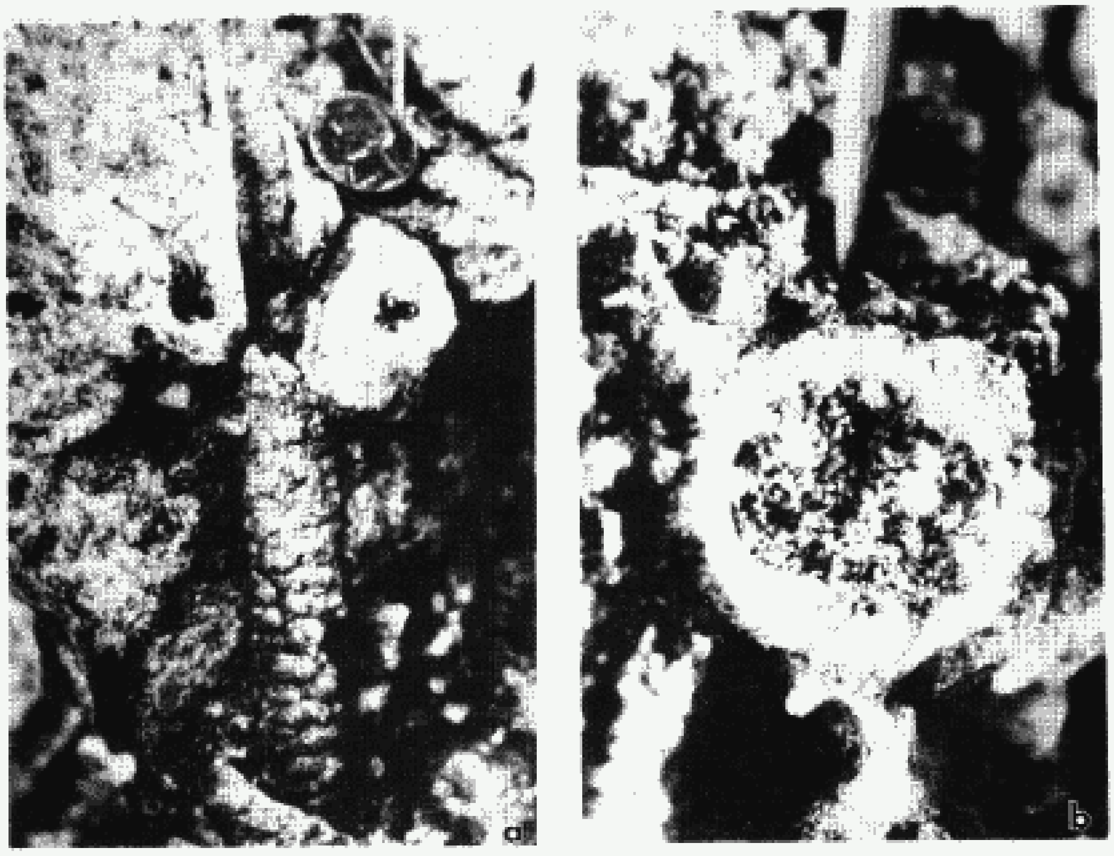


Figure 32. Callianassa sp. burrows: a) burrow exposed just above water level beneath bridge at Stop I. Note bumpy exterior of burrow lining and the mud-lined interior, typical of this animal's burrow; b) detail of mud lining of Callianassa burrow and typical coarse infilling of oolite. Relatively high permeability of burrow-fill sediment causes selective dissolution of infilling material.

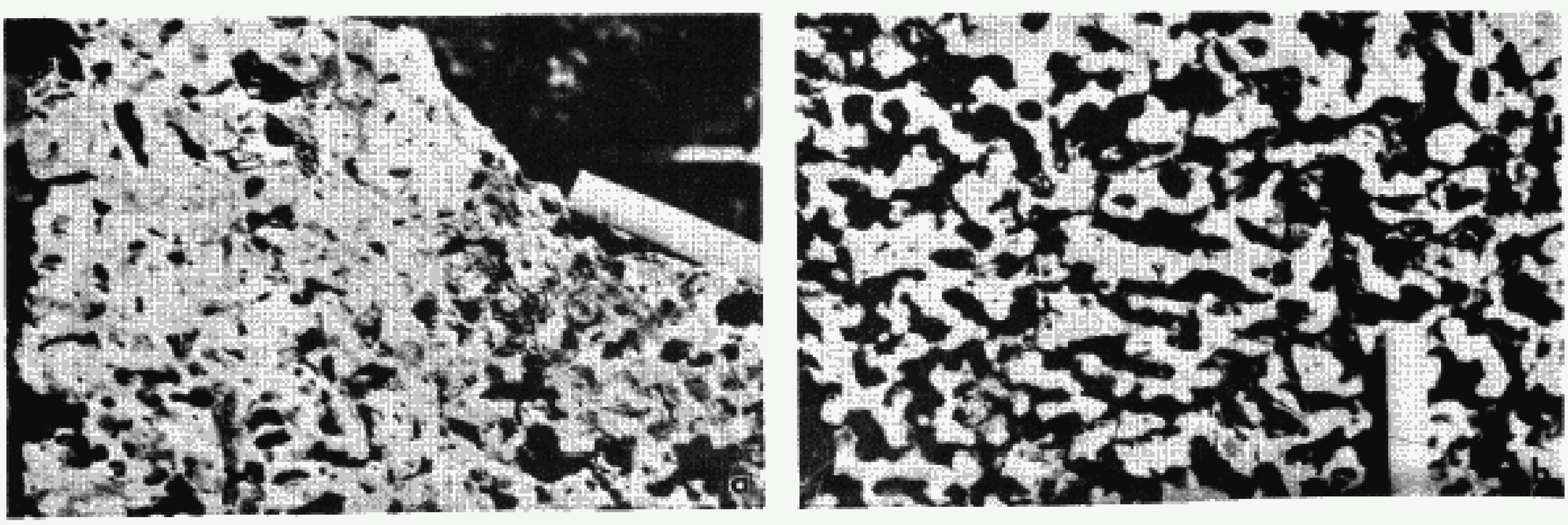


Figure 33. Rock slabs of burrow-mottled grainstones: a) slab contains both sediment-filled and unfilled burrows; b) slab in which all sediment has been dissolved from burrows. Bar scale is 15cm.

Both the cross bedded and burrowed facies of the Miami Limestone share this same early diagenetic change: what was originally relatively impermeable has preferentially cemented and become less permeable; what was originally more permeable has preferentially dissolved and become even more permeable. This style of diagenesis is characteristic of the Miami Limestone and is pursued further in the last section of the guidebook.

STOP II: SEA CLIFF EXPOSING CHANNELLED BAR
(1653 Bayshore Drive)

The exposure along the northwest side of Bayshore Drive at this locality is a portion of the Silver Bluff historic area and sampling is strictly prohibited. The exposure is approximately parallel to the trend of the active ooid shoal (normal to the trend of the exposure at STOP I). Along the base of the escarpment lies a very prominent cross set dipping 10° north of east at 26°. Much of the cross bedding at this locality is covered by a thin caliche crust which obscures the detail of the outcrop. Such crusts have been observed only on natural outcrops and probably require several hundreds, if not thousands, of years to form.

Channel Deposits

The southwest third of this outcrop exposes a concave upward second-order bounding surface in the upper half of the wall. It is seen to truncate strata beneath its right limb. The feature is about 5 meters wide and erodes at least 1 1/2 meters of the underlying sediments. The feature is interpreted as a filled tidal channel which trended at a high angle across the active ooid shoal (fig. 34).

Filled channels of various sizes are not uncommon in the upper portions of the active ooid shoal. A small channel is exposed along a driveway of a private home just east of STOP I (fig. 35) and another may be seen in a driveway, at additional Stop 5 (fig. 36). The channels are believed to have been transverse tidal channels which crossed the bar crest at various times during its development. Similar channels occur at irregular intervals along active seaward shoals in the Joulters Cays (fig. 29) and Cat Cays area of the Bahamas. The sediments filling these channels add to the complexity of interpreting cross bed direction in the Miami Limestone.

Silver Bluff

The escarpment at this locality is part of a more extensive low cliff, which occurs between the Miami River and Coconut Grove, and is termed Silver Bluff or the Silver Bluff terrace. We restrict our use of the term to the escarpment here and similar cliffs in the area.

Silver Bluff has received considerable attention in the literature. All writers agree that the feature is a wave-cut cliff but few agree on the age of the feature. It has been variously interpreted as Recent (White, 1970; Fairbridge, 1974), 18,000-45,000 years old (Hoyt and Hails, 1974) and as older Pleistocene in age.

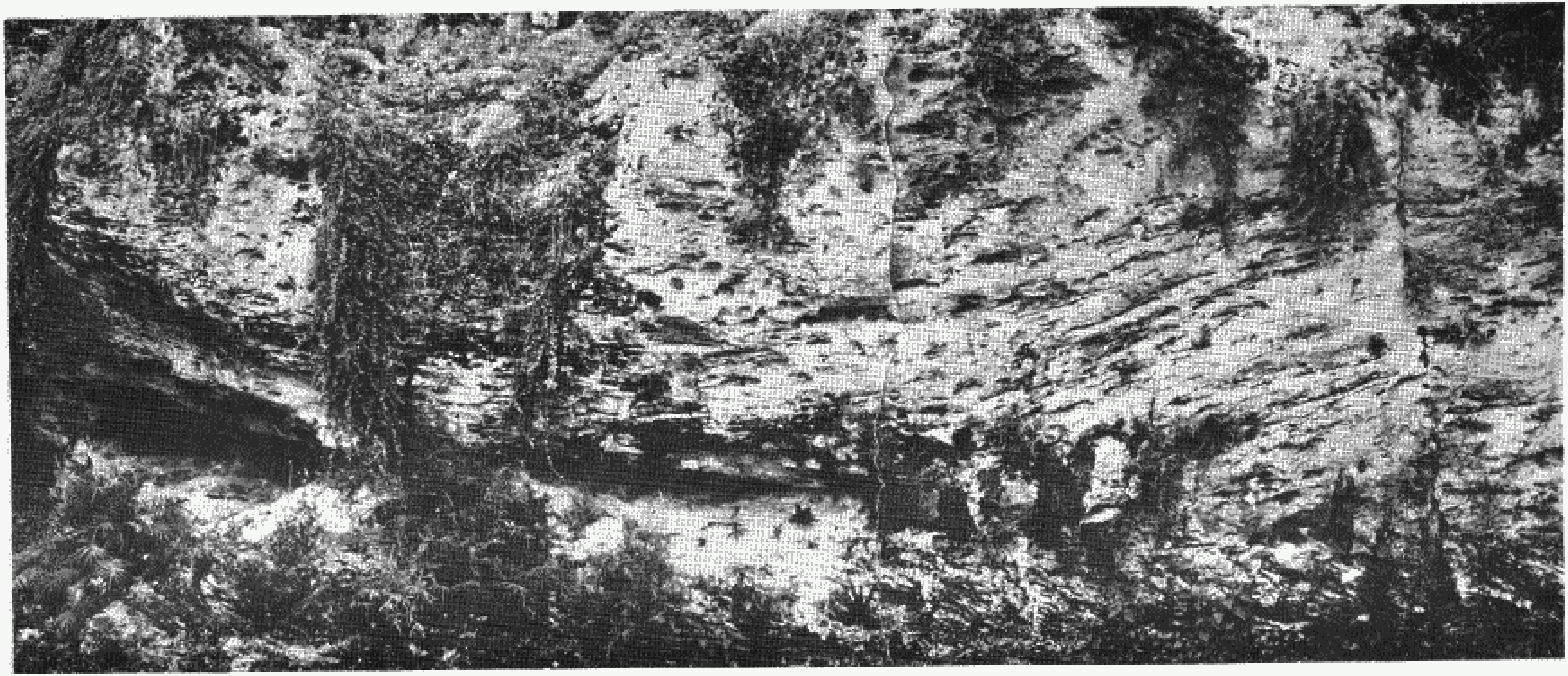


Figure 34. Channel exposed at south end of outcrop at STOP II. Note vertical joint at right side of illustration. Height of exposure is approximately 3m.

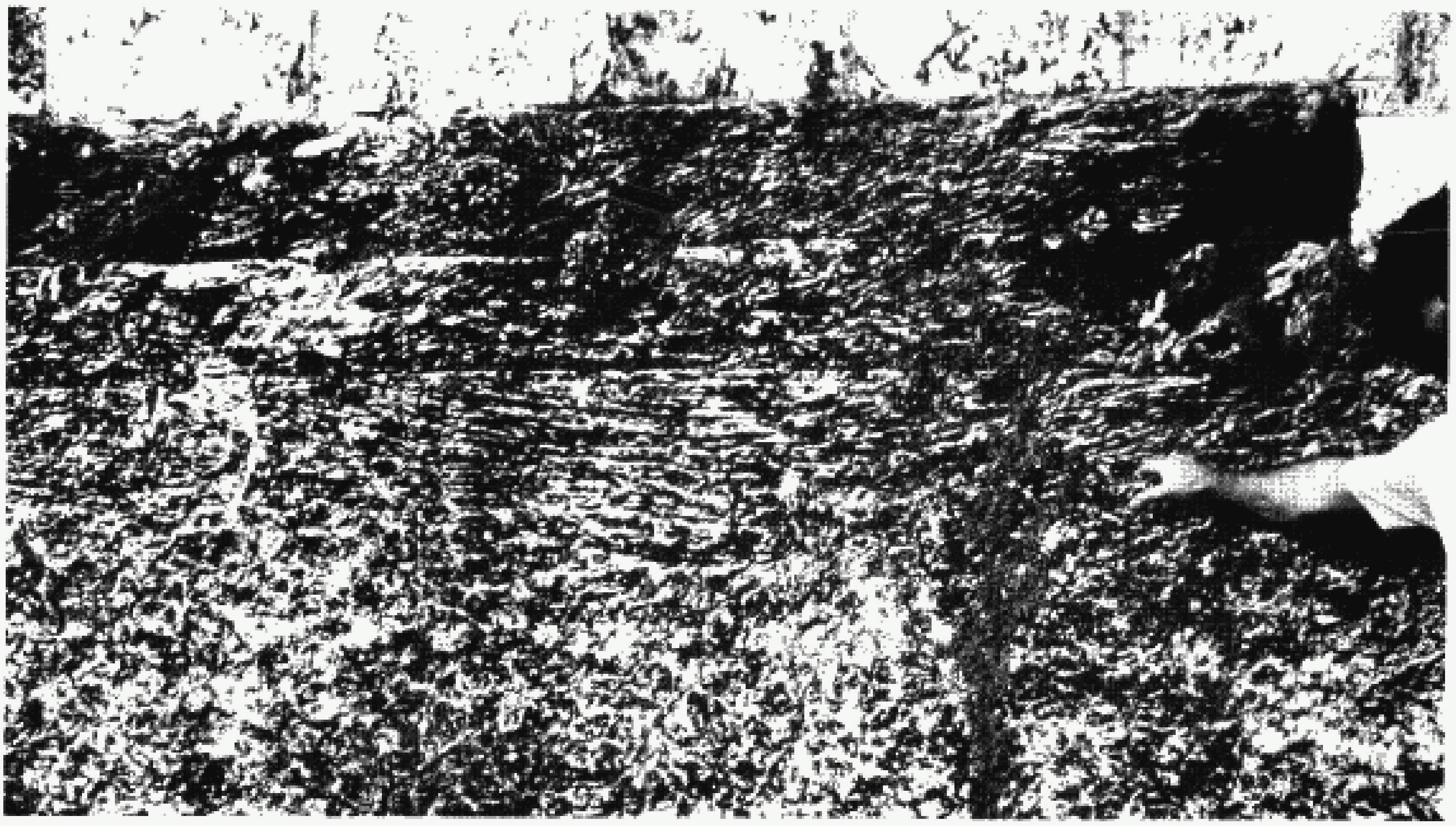


Figure 35. Small channel feature exposed in driveway about 100m east of STOP I.

Figure 36. Moderate-scale channel exposed along driveway at additional Stop 5.

A number of features have been cited by authors to argue their cases. White (1970) noted that the sea cliff at STOP II is within reach of modern storm tides and argued that the toe of this cliff was about at sea level based on the stratigraphy of fill seaward of the escarpment. He concluded the cliff to be of Recent origin. Only a few kilometers northeast of STOP II, waves lap against the base of Silver Bluff today (additional Stop 11, Appendix II). This area, about 50 meters long, is only a small portion of a considerable length of the escarpment which was being eroded along Biscayne Bay at the turn of the century (figs. 37-39). Most of this portion of Silver Bluff has been destroyed by coastal development, but in the area that remains, a well developed sea-level notch has formed, undercutting the cliff (fig. 40). No similar notch at the base of the escarpment exists south of Rickenbacker Causeway, suggesting that this portion of Silver Bluff has not been exposed to daily wave action recently.

We believe that the escarpment was cut in the Miami Limestone during sea-level fall shortly (a few thousand years) after the deposition of the Miami Limestone. We have arrived at this conclusion for the following reasons:

1) It seems to us unlikely that the cliff could have formed 35,000 years ago given present knowledge of Pleistocene sea-levels; at that time sea level was probably substantially below present sea level.
2) The authors know of no examples of similar sea cliffs cut in soft limestone that have formed at the edge of storm-driven tides as suggested by White (1970, p. 48); rather it appears as if a portion of a pre-existent escarpment has been reactivated in the recent past.
3) The escarpment is not at one elevation. An escarpment of similar form and weathering characteristics exists three to four meters above sea level at 120 SW 10th Street (additional Stop 5, Appendix II, fig. 41). We believe it is part of the evidence used by Parker and others (1955) to conclude that a 10-ft. escarpment existed in the Miami area. It seems possible to us that this cliff may be a continuation of the Silver Bluff cliff, rather than a separate escarpment. In either case, it is clearly <u>not</u> within reach of modern storm tides and must be a Pleistocene feature. Its similarity with Silver Bluff leads us to agree with the original interpretation that the cliffs are late Pleistocene.

We will argue from evidence presented at STOP V that portions of the Miami Limestone between Coconut Grove and the Miami River were lithified prior to the beginning of sea-level fall. This is a key element in our argument that Silver Bluff formed during sea-level fall about 120,000 years ago. That is, the Miami Limestone was lithified enough to be eroded by wave action along its east side only a few thousand years after its formation.

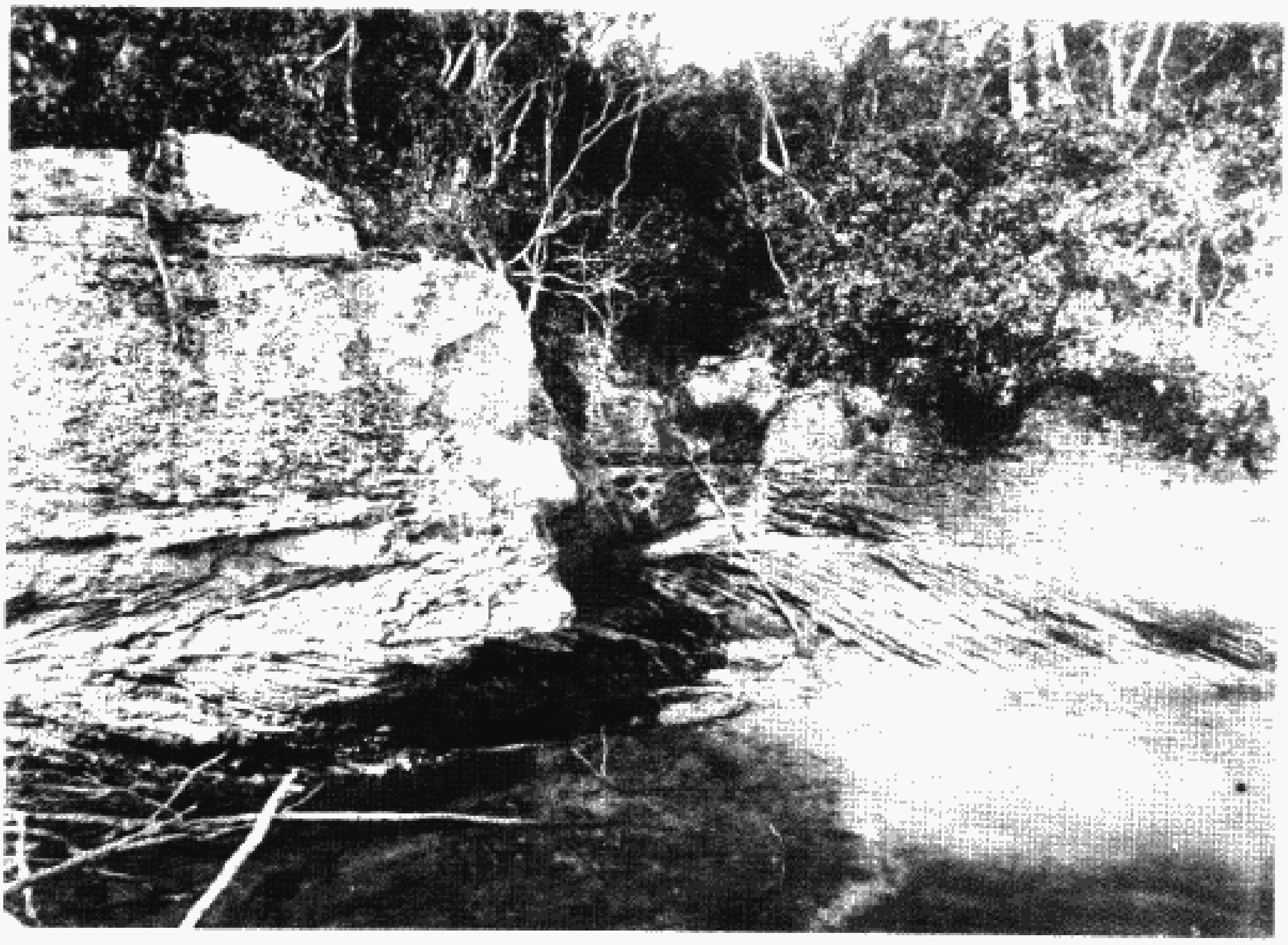


Figure 37. Outcrop exposed along Silver Bluff at the western shore of Biscayne Bay. Photo circa 1890. Here mottled facies overlies bedded facies as it does in Figure 52 at additional Stop 11. (Photo courtesy of Historical Association of Southern Florida.)

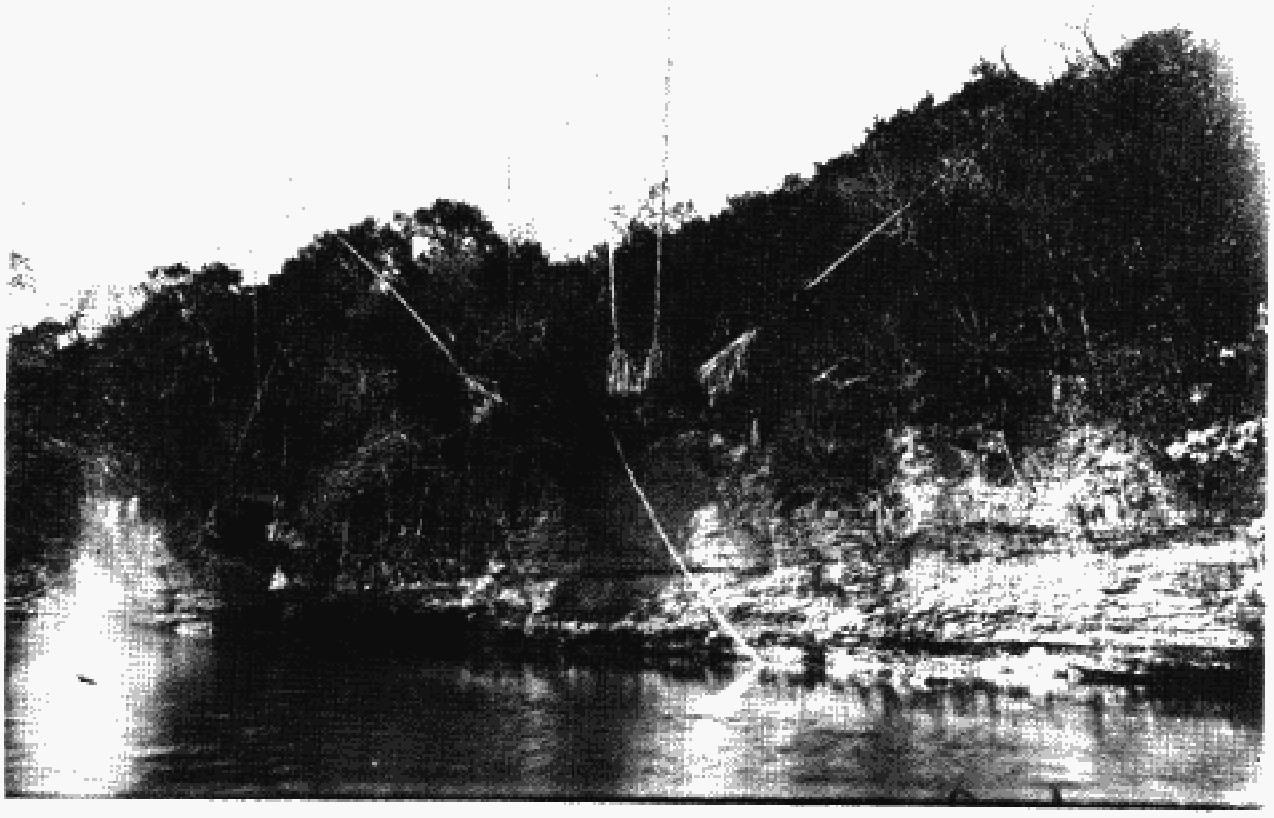


Figure 38. Silver Bluff outcrop along the shore of Biscayne Bay circa 1890. Note the undulating beds near the waterline on right side of photograph. Location somewhere between the Miami River and Rickenbacker Causeway. (Courtesy Historical Association of Southern Florida.)

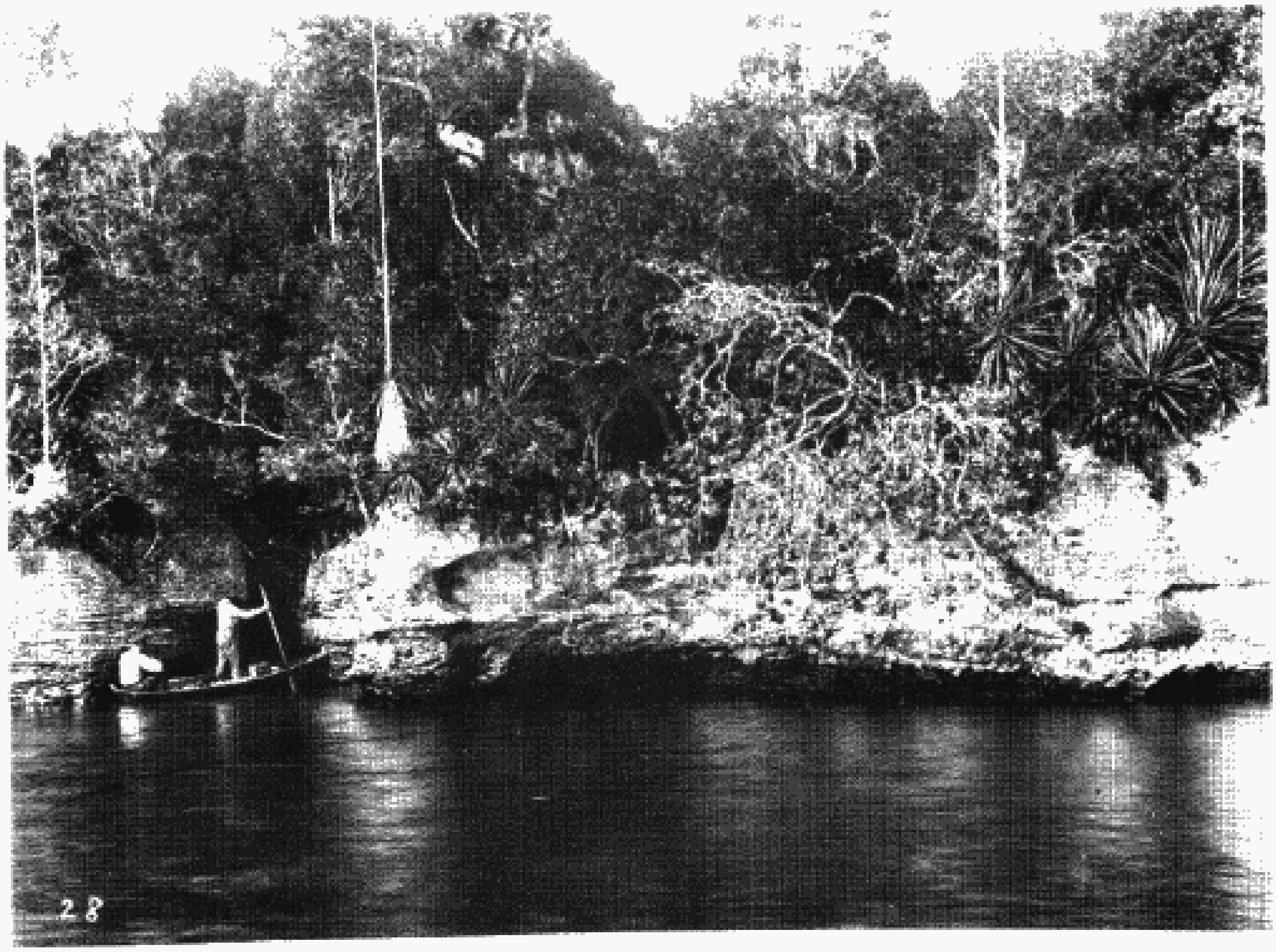


Figure 39. Silver Bluff outcrop along the shore of Biscayne Bay circa 1890. Here a well developed sea-level notch is visible at water level. (Courtesy Historical Association of Southern Florida.)

Figure 40. Silver Bluff outcrop at additional Stop 11. Arrows point to well developed sea-level notch which is more than one meter deep at some places along the cliff. Outcrop is about 2.5m high.

Figure 41. Sea cliff at additional Stop 5. The base of this feature is about 3 meters above sea level. Note the similarity of weathering and preservations to Silver Bluff at STOP II.

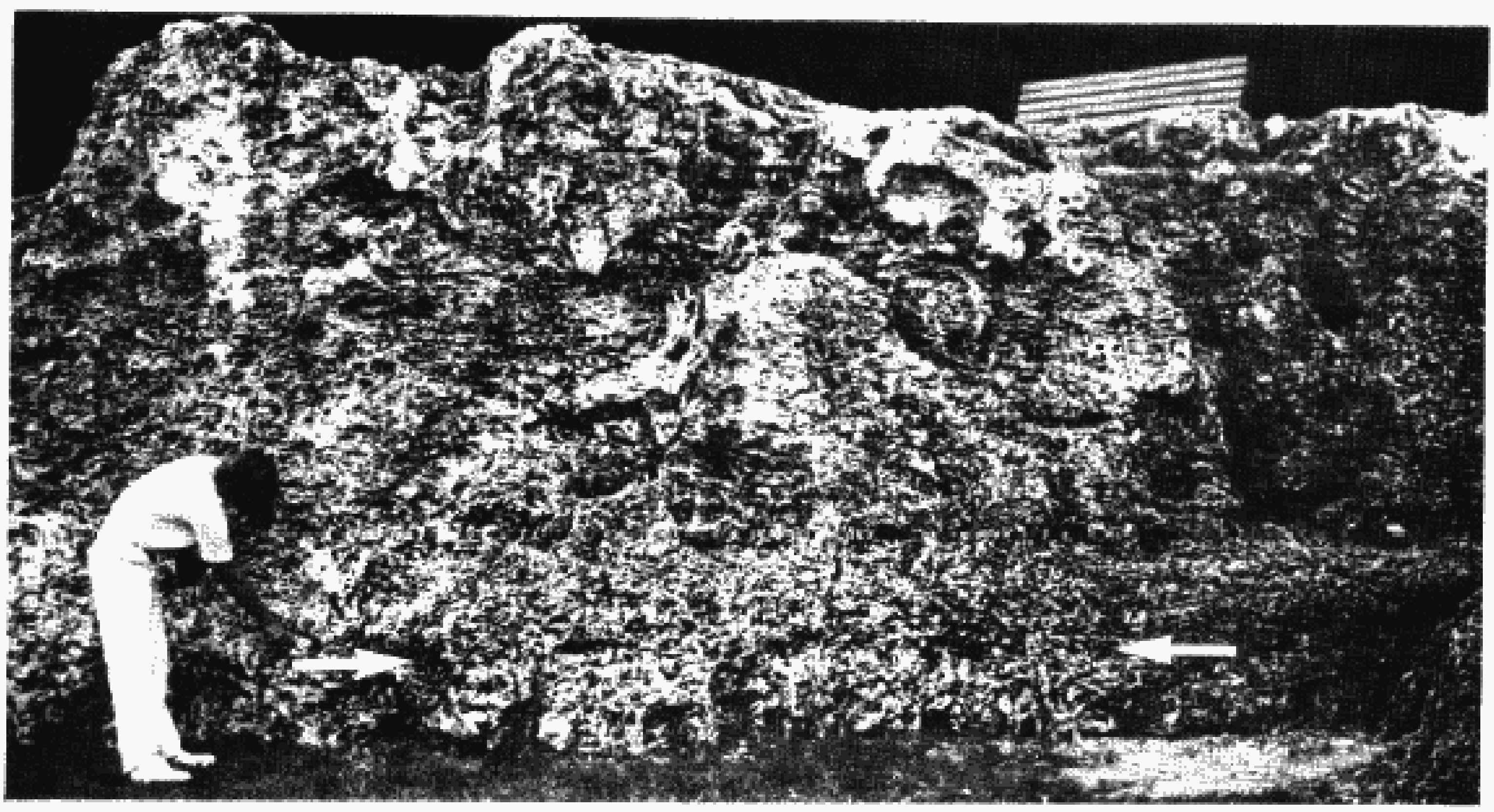


Figure 42. Portion of outcrop along Silver Bluff exposed in Alice Wainwright Park showing burrow-mottled grainstones and remnants of first-order bounding surface between arrows.

STOP III: SEAWARD STABILIZED SAND FLAT
(Alice Wainwright Park)

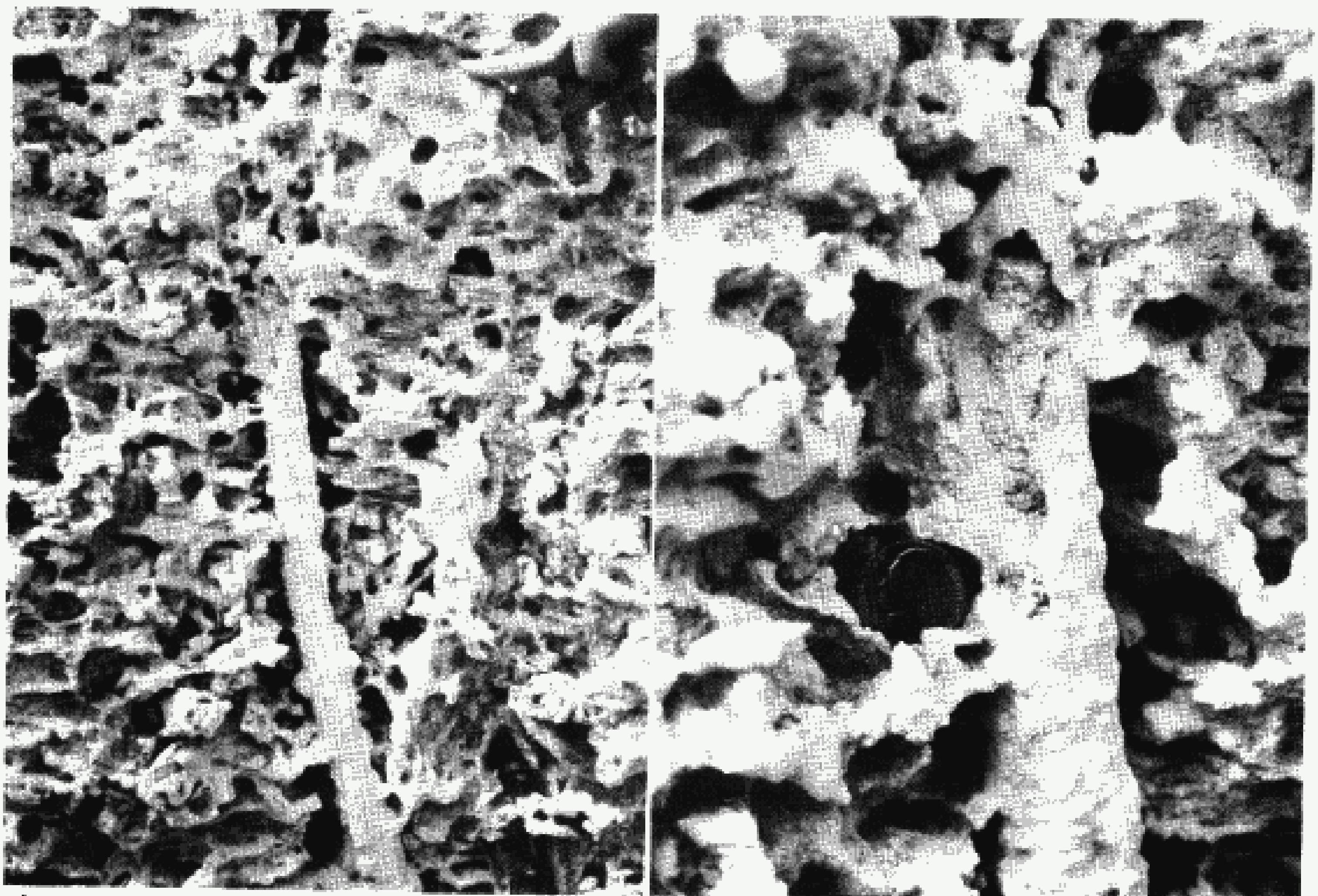
This outcrop is the northward continuation of Silver Bluff from STOP II. Although the escarpment here is similar to that at STOP II, the internal structure is almost entirely well burrowed. Traces of first-order bounding surfaces and foresets are present, particularly toward the base of the exposure (fig. 42), but burrows are the outstanding sedimentary structures of this outcrop.

The most common distinctive burrow here is that of a predominantly horizontal sediment feeder which leaves a burrow about 1 cm in diameter (fig. 43). *Callianassa* sp. burrows (the ichnogenus *Ophiomorpha* sp., fig. 44) and nested-cone burrows are present at this stop as well as a background of ubiquitous but less distinct burrows. The horizontal burrower, although unidentified, repacked sediment which was selectively cemented and weathers more resistively than the surrounding matrix. This burrow is typical of many outcrops from this locality north to the Miami River. Likely candidates for this horizontal sediment feeder are holothurians or annelids.

Traces of crossbedding visible near the base of the outcrop indicate that some, if not most, of the section exposed here was originally deposited as cross bedded ooid sand. Subsequent burrowing destroyed cross beds, probably by a combination of shallow burrowing soon after deposition and later burrowing by a deeper burrowing fauna. The abundance of burrows indicates a more stable, lower energy surface than that of active areas of an ooid shoal. Although a few burrowing organisms can survive the rigors of moving sands in the shallow parts of ooid shoals, for the most part, active shoals are deserts of the sea. In contrast, areas only a few meters away may be stabilized by sea grasses providing shelter for a variety of grazers and burrowers (fig. 29). In addition to sea grasses, stabilized sediment may be colonized by a variety of calcareous green algae, burrowing and grazing molluscs, echinoderms, and other organisms which supply a diverse skeletal fraction to the ooid sand. Burrowers mix this skeletal fraction with underlying ooid sands giving burrowed sediment more diverse grain composition than the original cross bedded ooid sands.

The presence of conchs (*Strombus gigas*) at this locality (fig. 45) also lends support to the interpretation of this area as a grass-stabilized sand flat. Conchs are commonly found wandering through modern sea-grass covered bottoms. Although only two of these fossils are present at this outcrop, they are the only two conchs of which we are aware in the Miami Limestone. Their presence here, although not conclusive, is to be expected and lends validity to our interpretation of this facies acquiring its final characterization in a stabilized, low-energy sand flat environment, seaward of the active barrier. Both at this stop and at STOP II, joints are exposed along Silver Bluff. Often, but not always, the joints are found at the back of re-entrants along the escarpment. These appear to have been points of weakness along the cliff and seem to have locally promoted erosion, possibly helping to form the re-entrants. One particularly angled joint is

Figure 43. Horizontal, sediment-filled burrows that characterize much of the Miami Limestone in Silver Bluff outcrops between Alice Wainwright Park and the Miami River. Marking pen is 10 cm long.



A B

Figure 44. Callianassa burrows: a) rough outer surface of mud lining; b) detail of (a) showing cross section of mud wall and coarse sediment filling interior of burrow.

Figure 45. Fossil conch exposed at top of outcrop near right side of exposure illustrated in Figure 42.

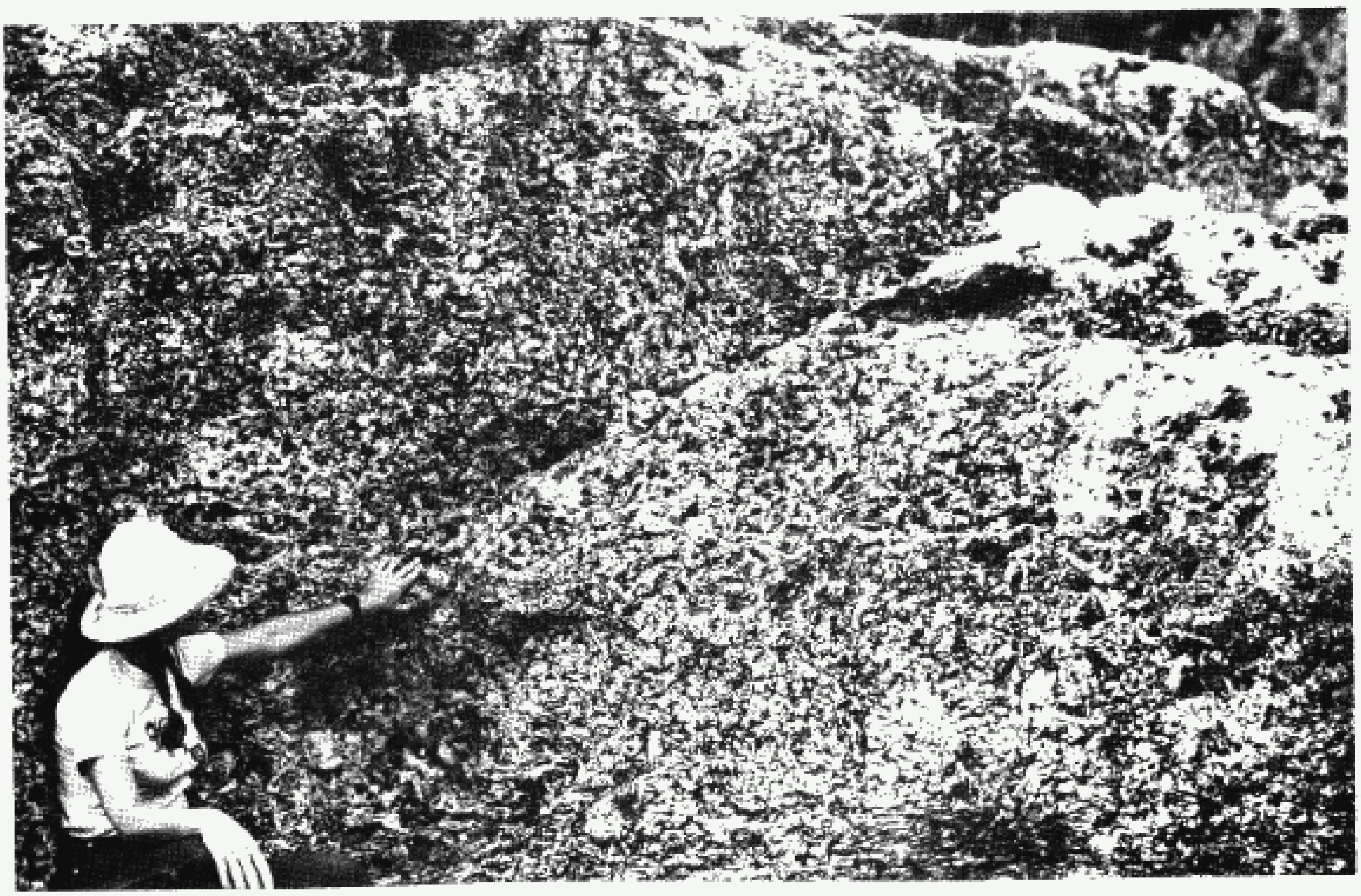


Figure 46. Portion of exposure at STOP III illustrating joint which is inclined at about 45 degrees.

shown in Figure 46 and another occurs on the right side in Figure 34. Because some joints seem to have affected erosion patterns along the cliff and others do not, we suggest jointing took place over a time span predating and postdating the formation of Silver Bluff.

STOP IV: PLATFORM INTERIOR SANDS AND THE BASE OF THE MIAMI LIMESTONE (Rinker Portland Cement Co., Tamiami Trail and 137 Street)

About 10 km west from the shore of Biscayne Bay the bedded ooid grainstone facies and the burrowed pelloid-ooid grainstone facies grade into byrozoan-rich pelloidal grainstones, the bryozoan facies of Hoffmeister and others (1967). These sediments were deposited as stabilized carbonate sands in deeper water (3-5 m) than the ooid shoals (0-3 m). At this stop we will examine this bryozoan facies and the base of the Miami Limestone. Because the elevations of this facies are generally about a meter above the water table, outcrops occur only along man-made excavations and usually face water. These are less than 1/2 meter high and are unsatisfactory for detailed examination. We follow the lead of many south Florida geologists and resort to studying blocks of rock that have been removed from nearby canals or rockpits. The boulders we examine at this stop come from Rinker Portland Cement Co. pits just to the north of this area.

The 31 boulders at this stop are of two types, labled M (Miami Limestone) and O (older) on Figure 47. The two types of boulders are quite distinct and a few minutes of examination allows easy differentiation of those which are Miami Limestone from the older rocks.

Miami Limestone Boulders

The Miami Limestone boulders are composed of burrowed bryozoan-rich, pelloidal grainstone. Many of the burrows are of the shape and size and have a mud lining typical of burrows made by *Callianassa* sp. Many features that superficially look like burrows, on closer examination, are bryozoan skeletons. These are the key features used for identification of the bryozoan facies defined by Hoffmeister and others (1967). They identified the bryozoan as the encrusting species *Schizoporella floridana.* In most examples of the bryozoa, a central canal is visible which is the void left after decay of the encrusted object, perhaps a sea-grass blade or a sponge. Continued growth of new bryozoan layers results in a rather knobby, irregular growth, often fist size

In addition to *Callianassa* sp. burrows, several blocks display back-filled burrows (fig. 48), not seen at other outcrops. Selective cementation has preferentially cemented some back-fill laminae, presumably fine-grained laminae.

At this locality the Miami Limestone is only 3 to 4 meters thick. The blocks here represent most of the unit and are typical of much of the formation in the Everglades. This facies is estimated to cover about 3,000 km^2 of the south Florida platform. The rock here is extremely bryozoan-rich, but this is not the case everywhere.

Particularly in the ooid shoal areas, burrowed facies do not contain abundant bryozoan skeletons. For example, the burrowed limestone below cross bedded oolite at STOP I contains very few bryozoan fragments, although many consider it the bryozoan facies. Besides having few bryozoans, outcrops of the burrowed facies to the east are composed of different constituent grains. At STOP I burrowed grainstones contain ooids, skeletal grains, pellets and pelloids. At STOP IV most sand size grains are molds, but of those that remain, almost all are pelloids. Pelloidal bryozoan grainstones directly comparable to these rocks are typical of modern platform interior sediments and cover vast areas of the interior of the Great Bahama Platform (Hoffmeister and others, 1967).

As discussed in the introduction, the bryozoan facies is not found beneath the ooid and pelloid-ooid grainstones of the Atlantic Coastal Ridge. Thus the bryozoan facies is not older than the sediments of the coastal ridge. The positive bathymetry established by the active ooid system to the east is directly responsible for the development of the protected, platform interior deposits of the bryozoan facies.

Older Limestone Boulders

The second type of boulder at this stop contains a variety of limestones. Besides grainstones and bryozoans, these rocks contain whole bivalves (commonly Chione canallata), corals (Montastraea sp.), and freshwater mudstones containing their own distinctive freshwater fauna. The freshwater limestone and associated subaerial crusts mark the base of the Miami Limestone (figs. 49 and 50).

The marine limestone underlying the Miami Limestone represents the upper part of the Fort Thompson Formation. The unit is late Pleistocene in age, but material suitable for radiometric dating has not been found in this area. The abundance of coral and diversity of other marine organisms in the unit suggest it is more open marine than the overlying Miami Limestone.

The contact between the two formations (Ft. Thompson/Miami Ls.) is very complex and involved several episodes of subaerial exposure. The upper surface of the marine limestone is a small-scale karst surface containing solution holes up to 30 cm deep. A subaerial crust coats portions of this surface. These crusts, first described from modern surfaces by Kornicker (1958) and from the subsurface by Multer and Hoffmeister (1968), represent a sea-level fall during the Pleistocene, probably as a result of the growth of continental glaciers.

Above the subaerial crust is a gray mudstone layer about 15 cm thick, containing gastropods and ostrocods, among other fossils. The color and texture of this layer make it a probable candidate for a freshwater limestone and the enclosed freshwater fauna, particularly the gastropods Heliosoma sp. and Pomaea sp., confirm this interpretation. The layer is an ancient analog for freshwater calcitic muds now accumulating in the Everglades (Gleason and Spackman, 1974). Criteria for recognition of freshwater limestones have been reviewed by Halley and Rose (1977). The freshwater limestone is, in turn, overlain by a subaerial crust, weathered and

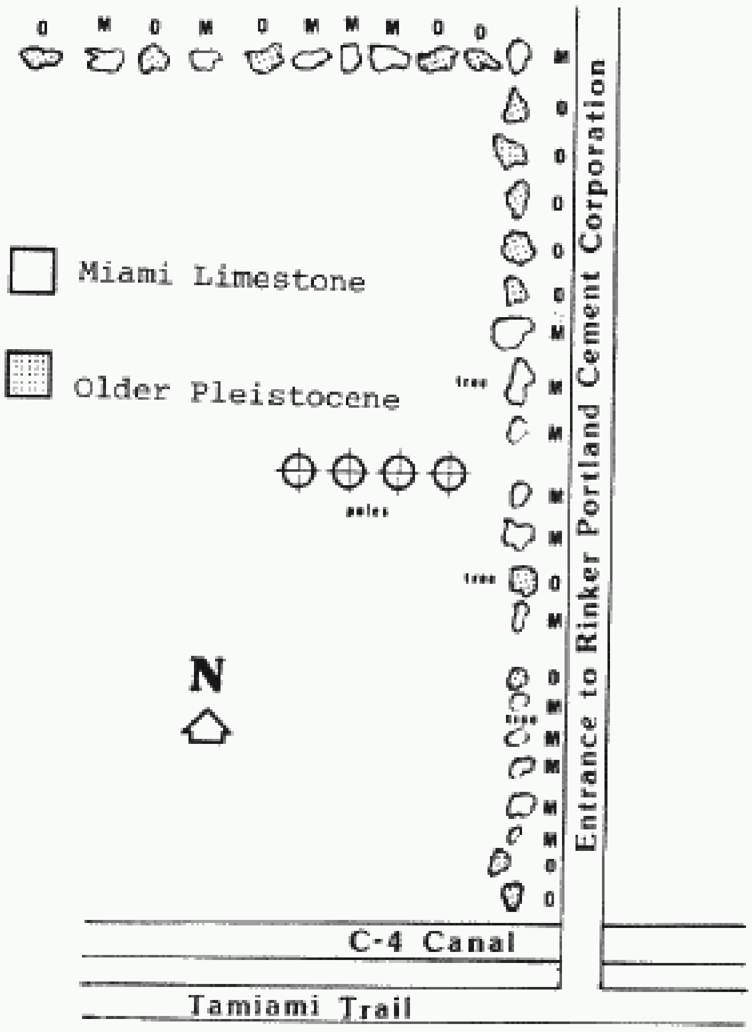


Figure 47. Sketch map showing position and type of boulders present at STOP IV. Not to scale.

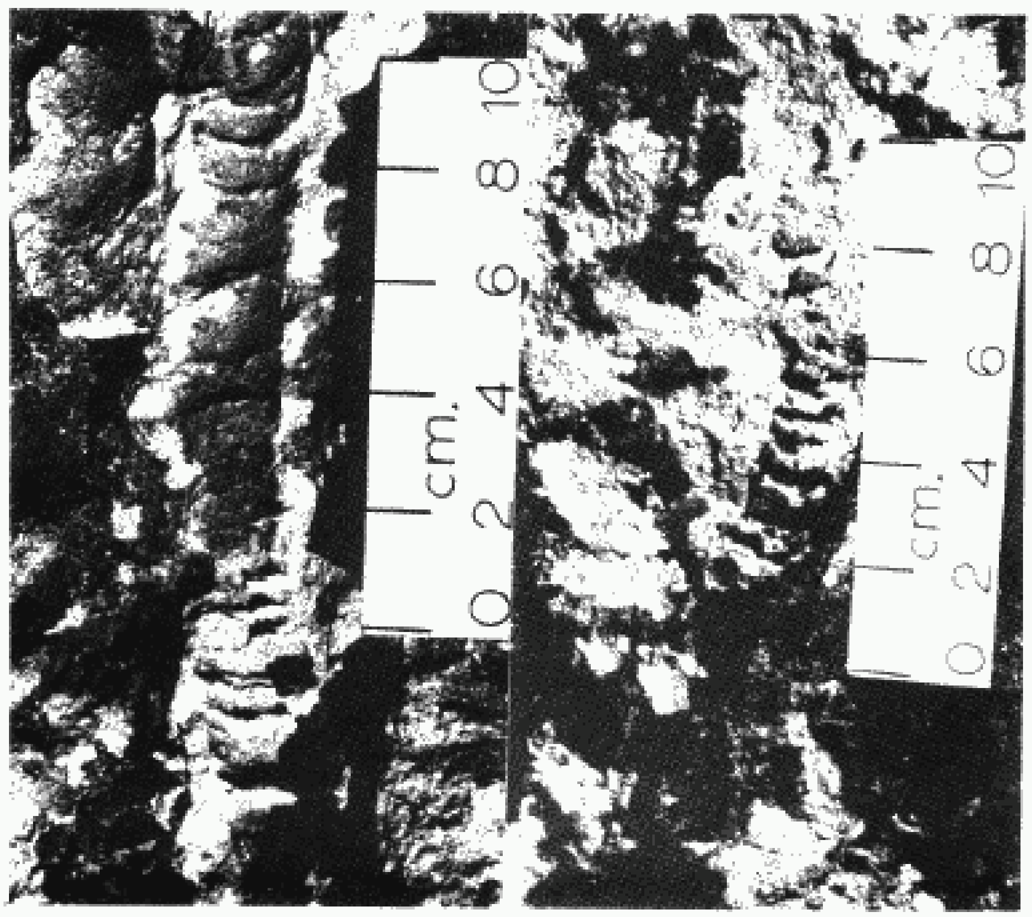


Figure 48. Back-filled burrows partially cemented and selectively weathered to reveal layers within the sediment that filled the burrow.

Figure 49. Limestone boulder dredged from the base of the Miami Limestone showing large dissolution vugs near base, dark clasts overlain by a thin dark subaerial crust which is in turn overlain by a layer of fresh water limestone. Bar scale is 15cm.

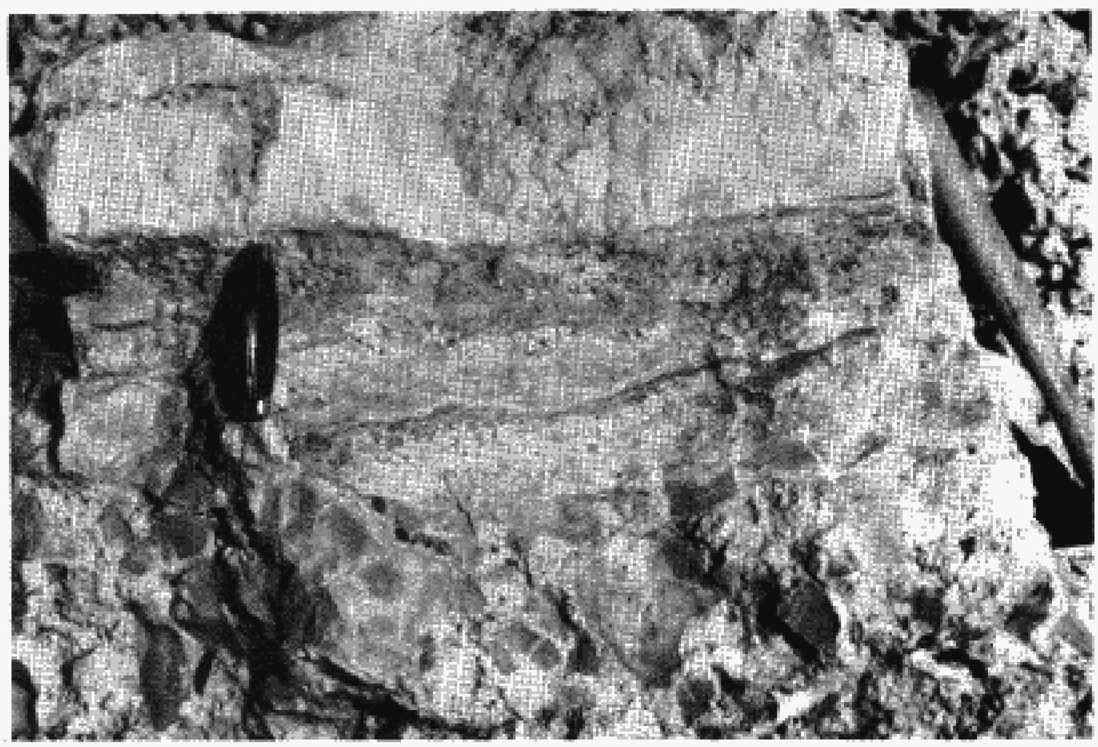


Figure 50. Limestone boulder similar to that shown in Figure 49 but with a well developed subaerial crust beneath penknife.

brecciated, indicating a second period of surface exposure. Clasts of the crusts and freshwater limestone fill solution holes developed in a second exposure surface less than 1 meter above the first. The basal sediments of the Miami Limestone overly this last exposure surface. The interlayering of laminated crust and freshwater limestone was produced during a single sea-level lowstand. During this time two episodes of crust formation occurred and were separated by a period of freshwater limestone deposition representing swamp (Everglades) environments.

STOP V: ISLANDS ON THE SHOALS
(1st Avenue and 13th Street)

The small roadcut along the north side of 13th Street and larger outcrops beneath the elevated railway to the west and north reveal features indicative of shoreline sedimentation within the Miami Limestone. Although these features do not pinpoint the location of a shoreline, they indicate the presence of shorelines and islands in the area as well as the diagenetic processes initiated by island development.

The most outstanding feature of this outcrop is the conglomerate exposed along the sidewalk (fig. 51). It is composed of blocks of cross bedded oolite (intraclasts) up to 50 cm across, cemented in an oolite matrix. Along with the oolite cobbles, other components of the conglomerate include bivalves (particularly the small shell Donax sp.), corals (Porites sp., Siderastrea sp. and Montastraea sp.) and bryozoan fragments. The largest clasts occur in outcrops facing 1st Avenue about 130 meters north of 13th Street. Here also is a piece of Montastraea cavernosa about 15 cm thick and 70 cm wide. The largest oolite block observed here is about 30 cm x 1 m x 2 m, a slab of friable, cross bedded oolite which could not have been moved far from its place of origin. This slab has recently been covered during construction. Many other clasts are so angular as to indicate little transport before final deposition.

Similar clasts occur at outcrops and in building excavations near the crest of the shoal from the Miami River to Coconut Grove (a distance of about 10 km, additional Stops 3 and 13, Appendix II). At STOP V, the conglomerate is about 5.5 meters above sea level, and all similar occurrences known to the authors are more than 4 meters above sea level.

The conglomerate overlies a 4-cm-thick micrite layer, perhaps a storm deposit which in turn overlies an erosion surface which dips seaward below the sidewalk (eastward). This erosion surface may be found in the outcrops beneath the railway where it can be shown to have more than one meter of relief (fig. 52). Oolite clasts and other debris are scattered above this surface.

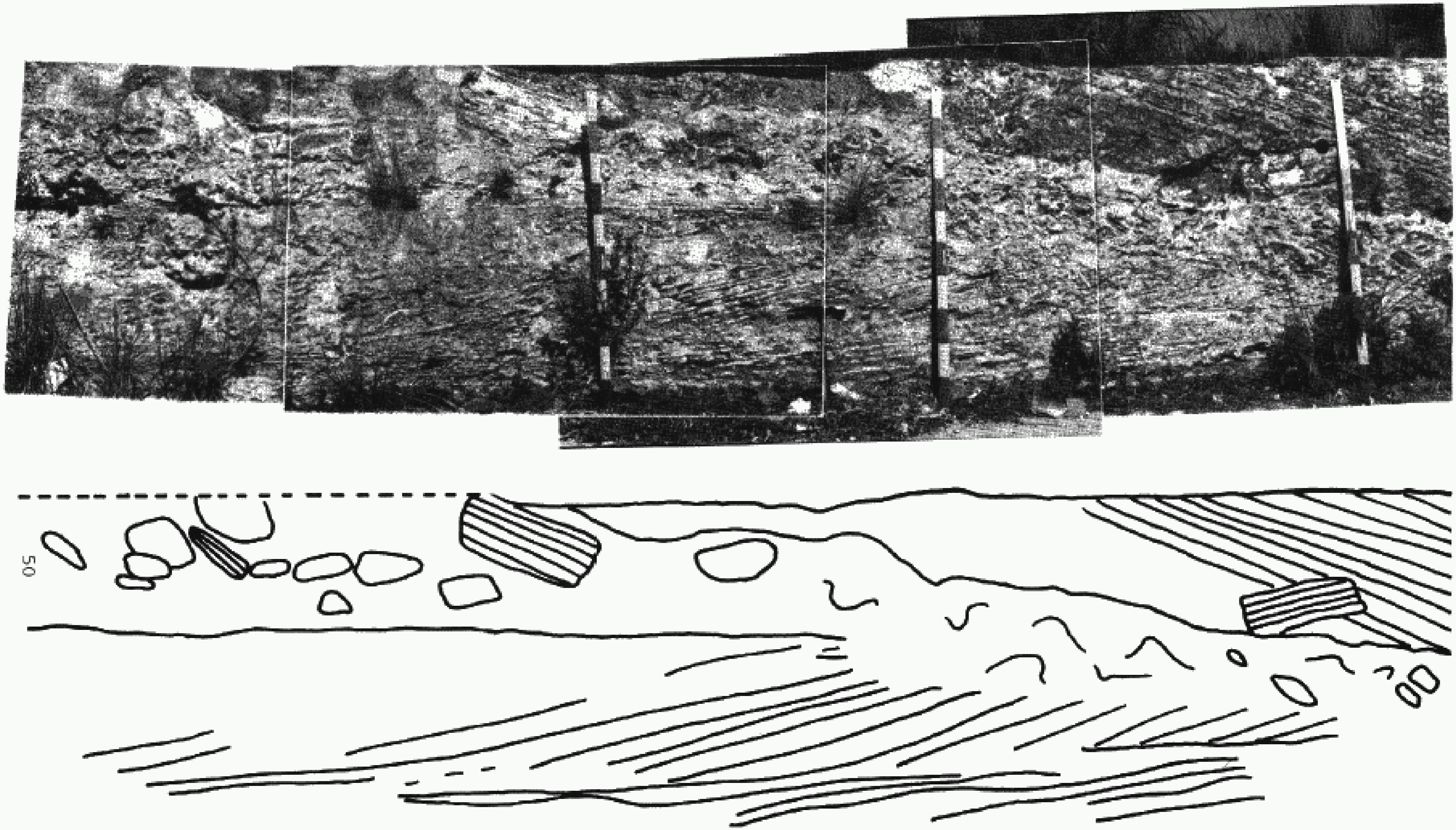


Figure 51. A photomosaic and line drawing of the outcrop at SW 2nd. Avenue and Coral Way (Stop V). A zone of coarse rubble made up largely of oolitic clasts with vadose cements in a micritic matrix overlies landward (westward) dipping beds. The rubble zone is overlain by gently seaward dipping beds. The presence of clasts of oolite cemented with vadose cement in a matrix of ooid sand indicates the presence of an island nearby during Miami Limestone time. The scale is 1 m with divisions of 10 cm.

Figure 52. Portion of outcrop at STOP V showing erosion surface that underlies horizon containing oolite clasts.

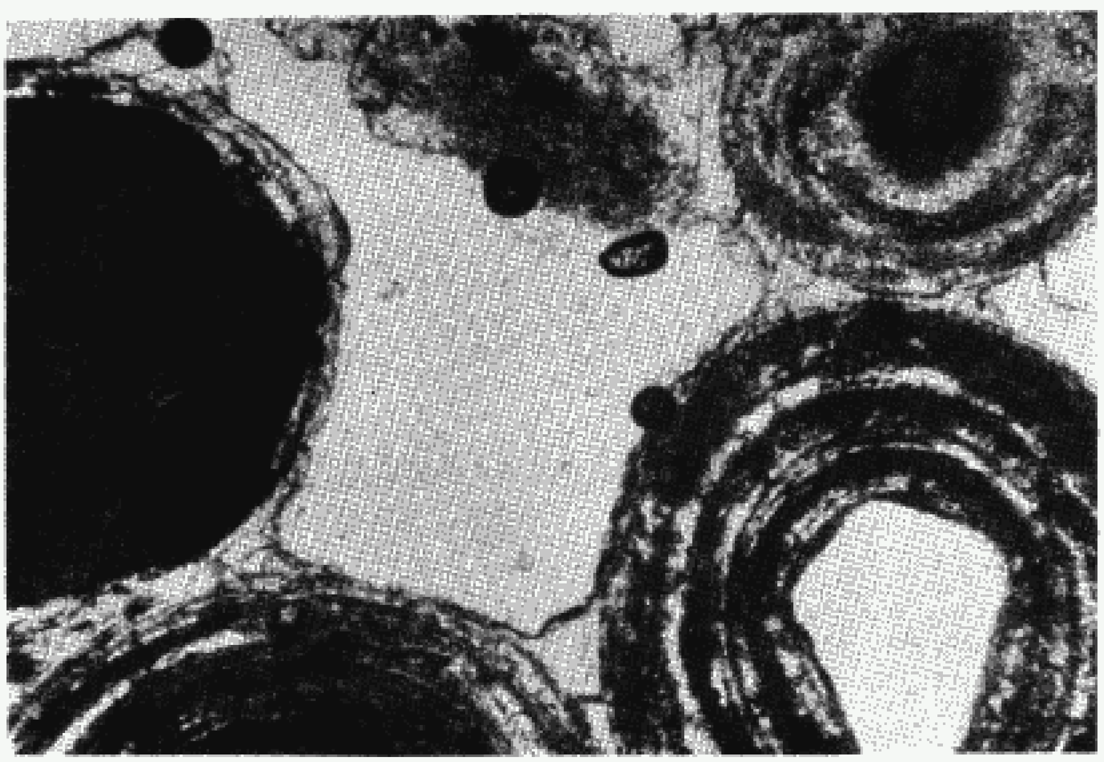


Figure 53. Photomicrograph of oolite from STOP V illustrating vadose-style cements between ooid grains. Width of photo represents 1.2mm.

Petrographic study of oolite clasts indicate they are lithified almost exclusively by vadose-style cements (fig. 53). Some show evidence of having been bored along their edges by marine bivalves Lithophagia sp. (fig. 54). The history of these clasts includes 1) cementation above the water table, 2) erosion and transport into marine water followed by boring and final burial, and 3) continued vadose alteration after sea-level fall. The first two steps in this sequence require no fluctuation of sea level, rather they may be a natural consequence of island building (Halley and Harris, 1979). Figure 55 illustrates these processes which are occurring today along the southeast shore of south Joulters Cay, Bahamas.

The highest beds exposed at this stop dip at low angles (5-18^{0}) toward the sea (east and northeast). Such low-angle, seaward-dipping beds occur at several outcrops at high elevations on the barrier bar (additional Stop 13, Appendix II) and are similar to low-angle beach or berm deposits (fig. 56). As with the cross strata illustrated in figure 22, however, well-cemented layers are thought to indicate only the general structure of these beds. The detailed, fine laminations needed to accurately identify the depositional environments of these rocks are obscured by selective cementation. Because of the association of these low-angle cross beds with eroded, redeposited clasts, a shoreline origin seems probable.

Besides the possible beach beds and clasts, a third shoreline feature is associated with the edges of these Pleistocene islands. These are the moderate size gastropods Cittarium pica (fig. 57). Known commonly as the West Indian top shell or the magpie shell, the snail is locally extinct in south Florida, although it thrives in rocky, intertidal zones in the Yucatan and West Indies (Abbott, 1974). The presence of these gastropods in association with other shoreline features supports our interpretation that this and other outcrops (additional Stop 3, Appendix II) in the area represent deposition at or near the edges of islands on the ooid shoals.

The establishment of islands late in the depositional history of the Miami Limestone, but before the next sea-level fall, created the opportunity for early lithification of parts of the formation. Early lithification in islands of ooid shoals may occur in less than 1,000 years (Halley and Harris, 1979). During this time, the growth of fresh- and brackish-water lenses beneath the islands may have cemented the sediment well below sea level. (A rough approximation of the ratio of thicknesses of fresh water above and below sea level in such lenses is 1 to 40 from the Ghyben-Hertzberg Relation.) It may be during this time that the phreatic cements, described at STOP I, formed at lower elevations within the formation. And it may be that it was during this brief phase of phreatic diagenesis that most cementation took place. Both Land (1970) and Steinen (1974) have argued that phreatic diagenesis is much more efficient than vadose alteration. By the time sea level began to fall, parts of the oolitic facies of the Miami Limestone were well cemented. The cementation was sufficient to cause jointing in the formation as the unit drained and underlying units consolidated. The cementation also sufficiently lithified the oolite so that small sea cliffs (Silver Bluff) could be carved from the rock at several levels as sea level dropped.

Figure 54. Holes (arrows) made by boring clams around the edges of oolite clasts prior to burial in ooid sand and further lithification of the Miami Limestone.

Figure 55. Part of the eroding shoreline of south Joulters Cay where clasts of Holocene oolite are being eroded from the sea cliff and buried in ooid sands of the modern beach. Escarpment is about 3m high.

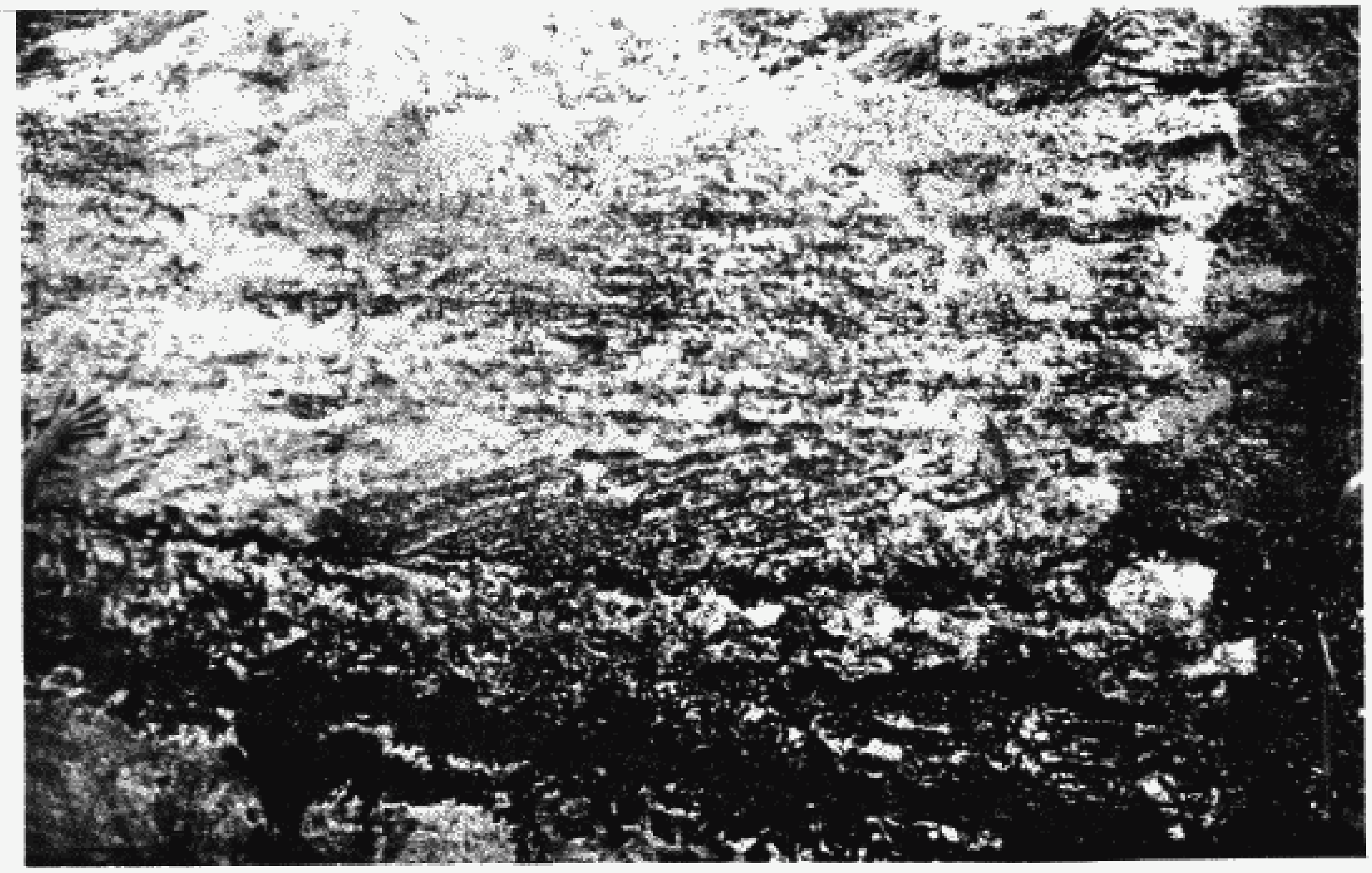


Figure 56. Low-angle, eastward-dipping, beach(?) beds at the highest elevations of STOP V. They overlie more steeply dipping crossbedded oolite which is typical of the bedded facies.

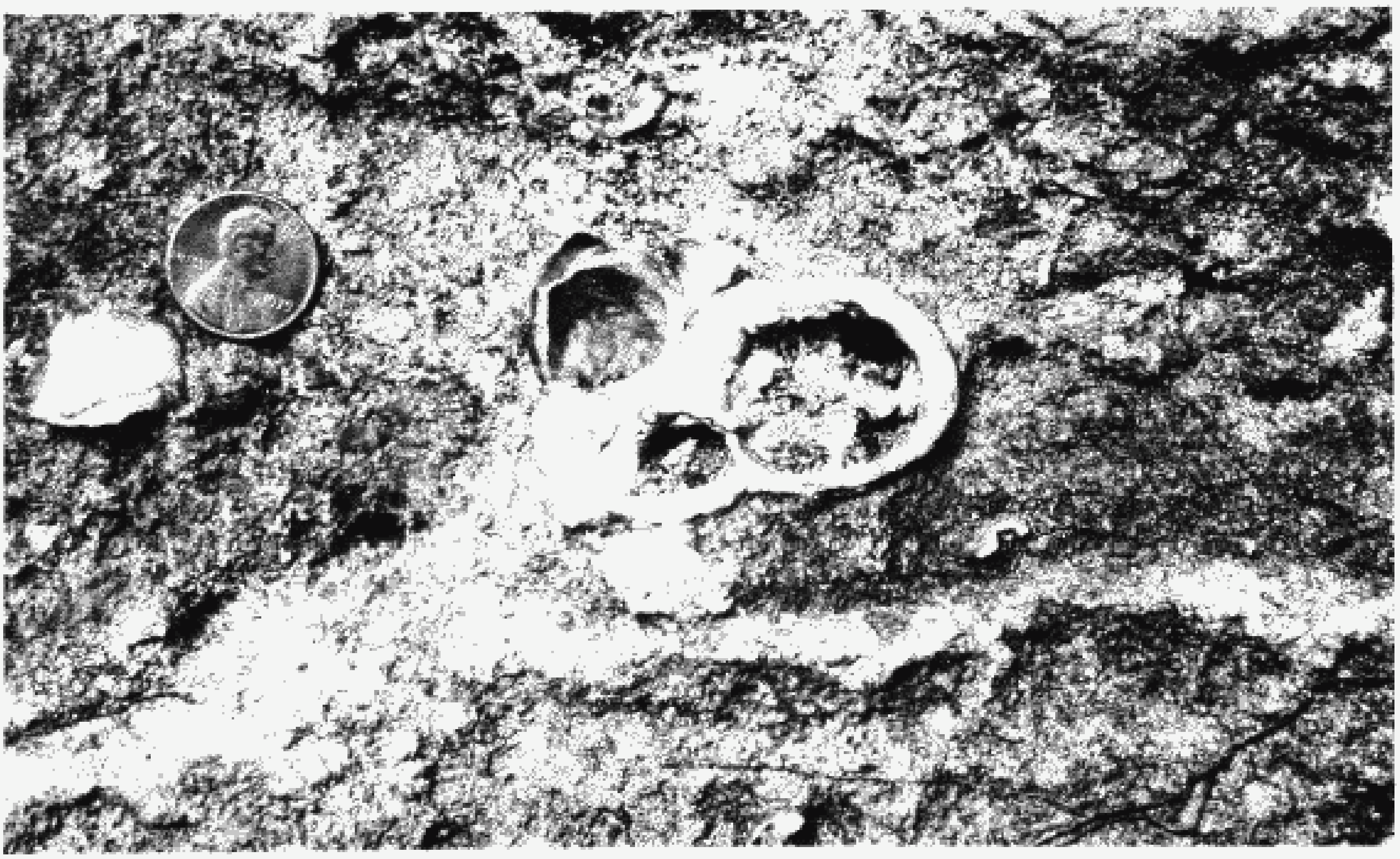


Figure 57. Fossil West Indian top shell embedded in the Miami Limestone at additional Stop 3.

SIGNIFICANCE OF DIAGENESIS WITHIN THE MIAMI LIMESTONE

Recent shallow-water, marine, carbonate sediments are composed largely of the metastable carbonate minerals aragonite and a variety of calcite containing more than 4 percent $MgCO_3$ (high-magnesium calcite). These sediments also have extremely high porosity, typically 45-50 percent for carbonate sands and 70-80 percent for carbonate muds. In contrast, typical ancient carbonate rocks are composed of calcite and dolomite and only a few percent pore space. The Miami Limestone represents an example of a unit in transition from modern sediment to ancient limestone.

Although it is still possible to find areas where the Miami Limestone is more than 75 percent aragonite, for example at STOP V, an average for the unit is about 15 percent aragonite (fig. 58). This is not substantially different from most equivalent Pleistocene limestones which have largely altered to calcite during freshwater diagenesis. Similar mineralogical changes and the associated petrographic alterations have been documented on Bermuda (Land, 1967), Barbados (Matthews, 1967), and on several Bahama islands as well as in the Miami area (Friedman, 1964; Robinson, 1967).

South Joulters Cay is an example of aragonitic sand just starting this transition, and only about 10 percent of the aragonite has been converted to calcite (Halley and Harris, 1979). Aragonite is dissolving in the freshwater lense of south Joulters Cay and calcite cement is precipitating in primary pore spaces. These processes roughly compensate for each other so that, although there is a change in the character of pore space from primary to secondary, the total volume of pore space stays about the same (Halley and Beach, 1979).

A similar conservation of total pore space occurs in the Miami Limestone, although porosity is much more difficult to measure in this formation. The measurement of vuggy porosity in particular requires special techniques, as pointed out in Figure 59 and discussed by Halley and Schmoker (1983). Evans (1982) found a general porosity increase with depth in the Miami Limestone (fig. 60) averaging to about 45 percent for the formation.

Figure 61 illustrates concepts which help put the Miami Limestone in perspective relative to the development of typical ancient carbonate rocks. It is clear from the figure that the average total porosity volume of the formation has not changed much from that of unconsolidated ooid sand. Thus, although the mineralogy has been largely stabilized, the rock has not started to acquire the low porosity typical of ancient carbonate rocks. It is also evident from Figure 61 that the wide range of porosity values reflects the development of vuggy porosity. Vuggy porosity develops as a result of dissolution and cementation patterns that are controlled in large part by permeability differences in the original sediment. As discussed at STOP I, the least permeable portions of the rock are cemented and become tight, whereas the more permeable portions are selectively dissolved to develop vuggy porosity. This trend records the beginning of karst development and internal dissolution and precipitation leading to larger and larger pores surrounded by less and less porous matrix material. Thus, although the mineralogical trends of

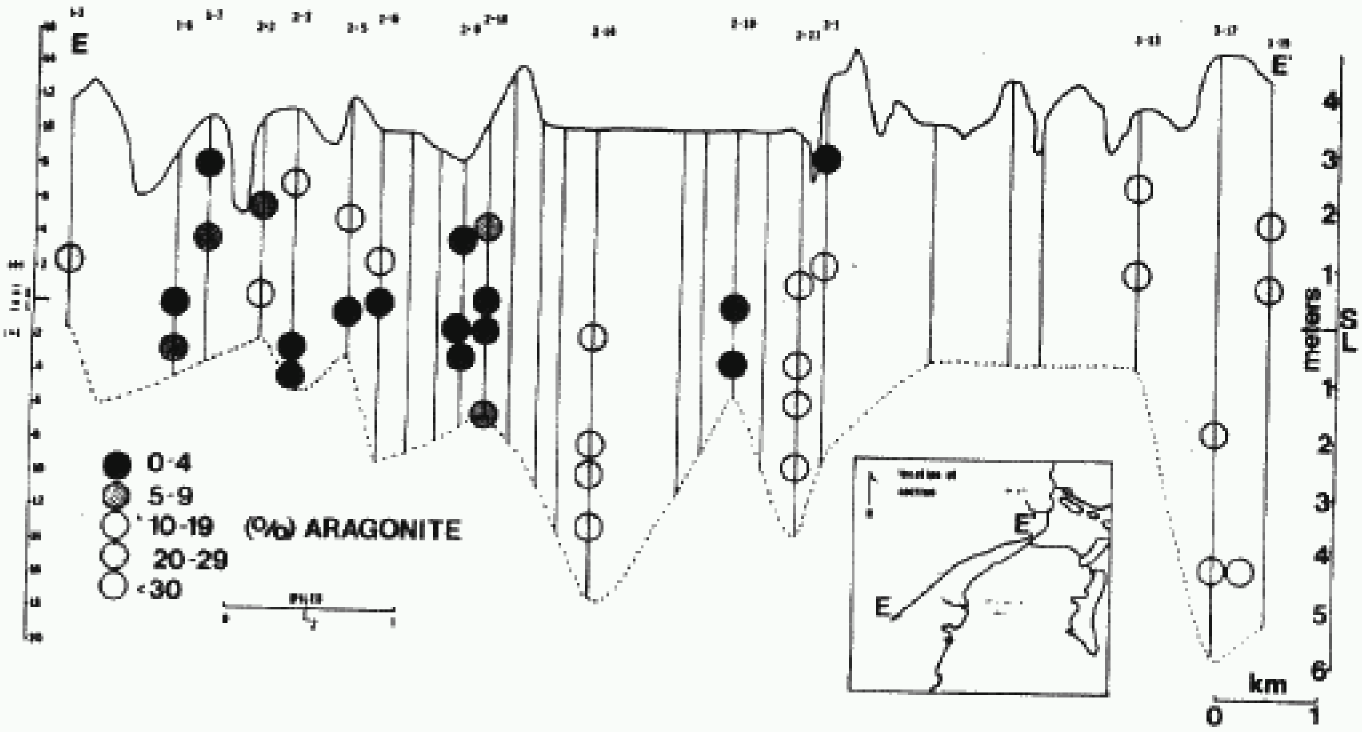


Figure 58. Distribution of aragonite in cores from the Miami Limestone (from Evans, 1982).

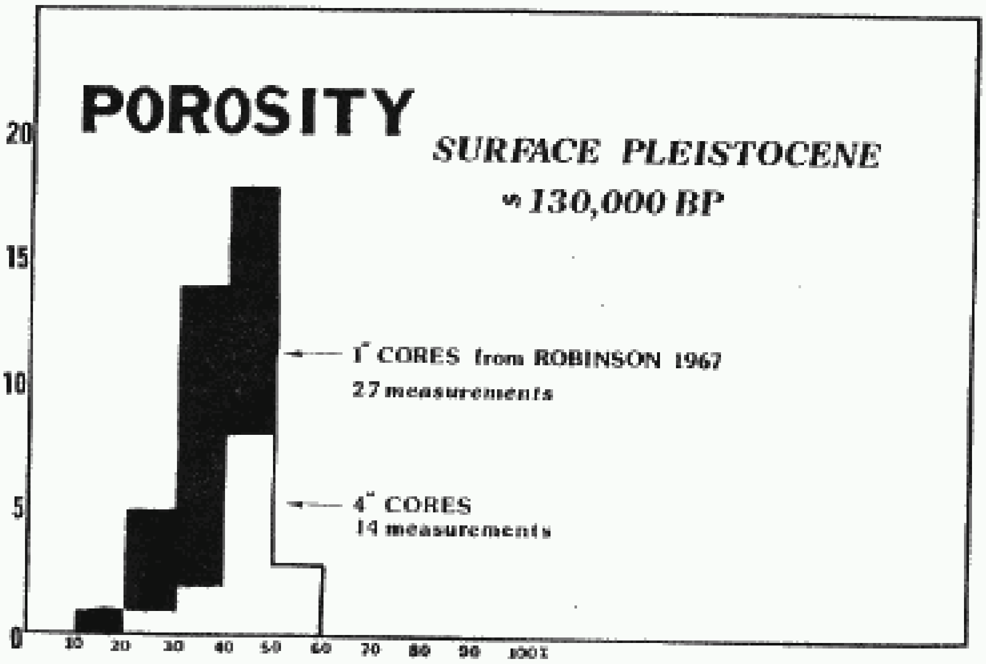


Figure 59. Porosity of the Miami Limestone as measured by two methods. Measurement in small cores (black) fails to incorporate vuggy porosity and underestimates porosity. Measurement in larger cores (white) samples more of the vuggy porosity for an average value of 45 percent.

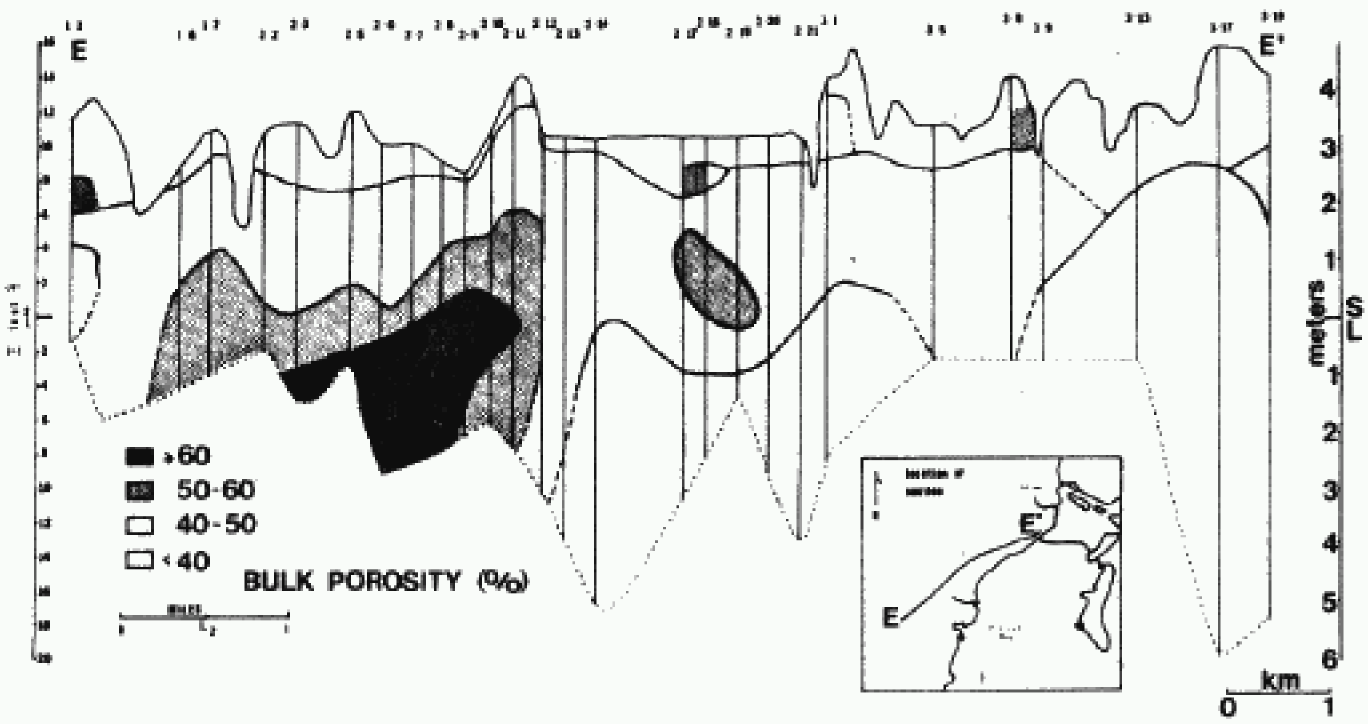


Figure 60. Porosity distribution in cores of the Miami Limestone (from Evans, 1982).

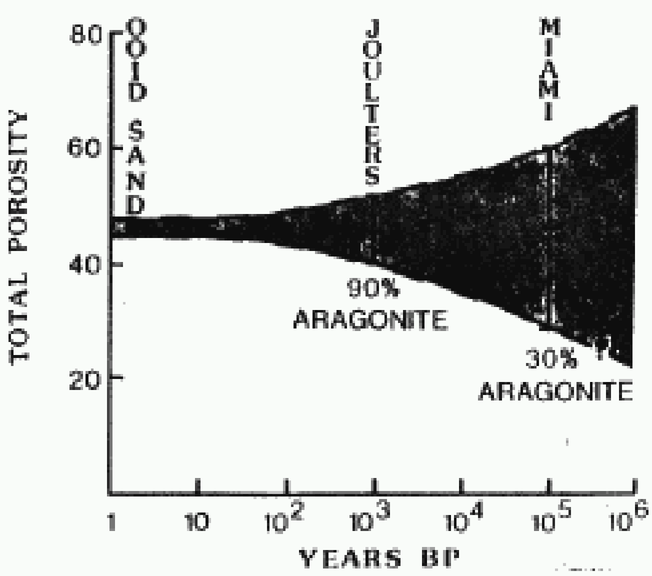


Figure 61. Diagram illustrating lack of porosity change during mineralogical stabilization of oolites in Florida and the Bahamas. A modern unconsolidated ooid sand is illustrated at the left of the diagram with about 45 percent porosity and 100 percent aragonite. On Joulters Cays about 10 percent of the aragonite has been converted to calcite cement causing a wider range of porosity measurements, but the average porosity is still about 45 percent. The oolite facies of the Miami Limestone retains only about 30 percent aragonite, the other 70 percent having been converted to calcite. It has also developed vuggy porosity causing individual porosity measurements to span a wide range, but the average porosity is still about 45 percent.

the Miami Limestone are leading towards a composition typical of an ancient carbonate rock, the porosity trends of the formation are not. Rather, the unit appears headed for increased karstification as long as it is exposed at the surface. It would appear that significant porosity loss in south Florida carbonates does not begin until carbonate rocks are carried into the subsurface by continued subsidence and sedimentation (Schmoker and Halley, 1982; Halley and Schmoker, 1983).

SUMMARY

This field guide provides a broad overview of the depositional settings and diagenetic history of the Pleistocene-age Miami Limestone. The field stops indicate that deposition was in a near shore, shallow water marine environment as part of a barrier bar complex with a more protected shoal and channel system bankward of the barrier bar. Cementation occurred both in a vadose and phreatic environment with possibly the bulk of cementation taking place during phreatic conditions.

The Miami ooid system probably originated as an arcuate array of shoals and channels with the long axis of the individual shoals and channels oriented perpendicular to the shelf break. A modern analog of this setting is found near Joulters Cay, Bahamas. In its modern setting this morphology is established and maintained by tidal pumping on and off the shelf platform.

As the ancient ooid system grew, ebb tidal deltas formed on the seaward face of the system, eventually reshaping the pre-existing coast-normal morphology into a barrier bar. The reshaping was the result of coalescence of the individual tidal deltas. The barrier, which occupied the seaward-most position, was oriented parallel to the shelf break. This ooid system now comprises the major positive topographic feature in the Miami area, the Atlantic Coastal Ridge.

The sedimentary record of the barrier depicts multi-directional movement of large, sinuous crested sand waves across the barrier (Stop I). The migration of sand waves was interspersed with periods of scour, concentrating skeletal material by winnowing, as evidenced at first order bounding surfaces. Evidence of channelling within the barrier is found at Stop II. The periods of active sedimentation and erosion alternated with periods of much reduced sedimentation. These latter periods are characterized in the sedimentary record by a mottled sediment fabric produced by an active burrowing fauna. The ichnofabric, which developed from the burrowing, is in evidence at Stops I through III.

Further development of the barrier system restricted circulation in the shallow-water back barrier region. The restriction in circulation was most pronounced to the north with significantly less influence toward the south or terminus of the barrier. Behind the ooid system a bryozoan community was established on the interior platform (Stop IV).

Along the barrier several subaerial islands were developed (Stop V). These islands housed small lenses of ground water which provided the mechanism for cementation. These lenses may have cemented the sediment well below sea level. This early cementation of the ooid sand provided a competent rock unit which, when subjected to wave cutting, produced the sea cliffs observed at Stops II and III. The sea cliffs are believed to have been initially formed while portions of the ooid system were still active. This argues that the sea cliffs, so dramatically displayed at the Silver Bluff (Stop II), are of a geologically simailar age as the deposition of the barrier sands.

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APPENDIX I
Historical Summary

Early reports having to do with the geology of the Miami area include reports from late 18th century sailing vessels of low sea cliffs south of the Miami River and scattered reports of limestone deposits by U.S. Army officers during the Seminole Indian wars. Buckingham Smith (1854) noted that shells in these limestone deposits were post-Pliocene. Toumey (1851) gives a first account of outcrops along the Miami River but the presence of oolite rock was not described until 1862 by Hunt. Louis Agassiz (1852) described the rocks of the Miami area as reefal in origin and Shaler (1890) followed this interpretation and included the oolite in his "Miami Reef." Alexander Agassiz (1895 and 1896) clearly differentiated the oolite deposits and believed them to be of aeolian origin. Griswold (1896), however, determined the bulk of the oolite deposit to be marine.

Sanford (1909) formally named the Miami Oolite and differentiated it from the Key West Oolite, a name he used for the oolite cropping out in the lower Florida Keys. Cooke and Mossom (1929) combined both oolite occurrences into the Miami Oolite and presumed the unit to be continuous beneath Florida Bay as did Parker and Cooke (1944, p. 70). Hoffmeister, Stockman and Multer (1967) described an oolitic, pelletal, burrowed, bryozoan-rich facies of the Miami Oolite which was laterally equivalent to and underlies the cross bedded oolite facies. They group the two facies together, renaming the unit the Miami Limestone. Mitchell-Tapping (1980) again separated the Miami Oolite, which he renamed the Fort Dallas Oolite, from the Key West Oolite, a practice we do not follow here. We recognize the oolitic facies of the Miami Limestone in the Miami and Key West areas.

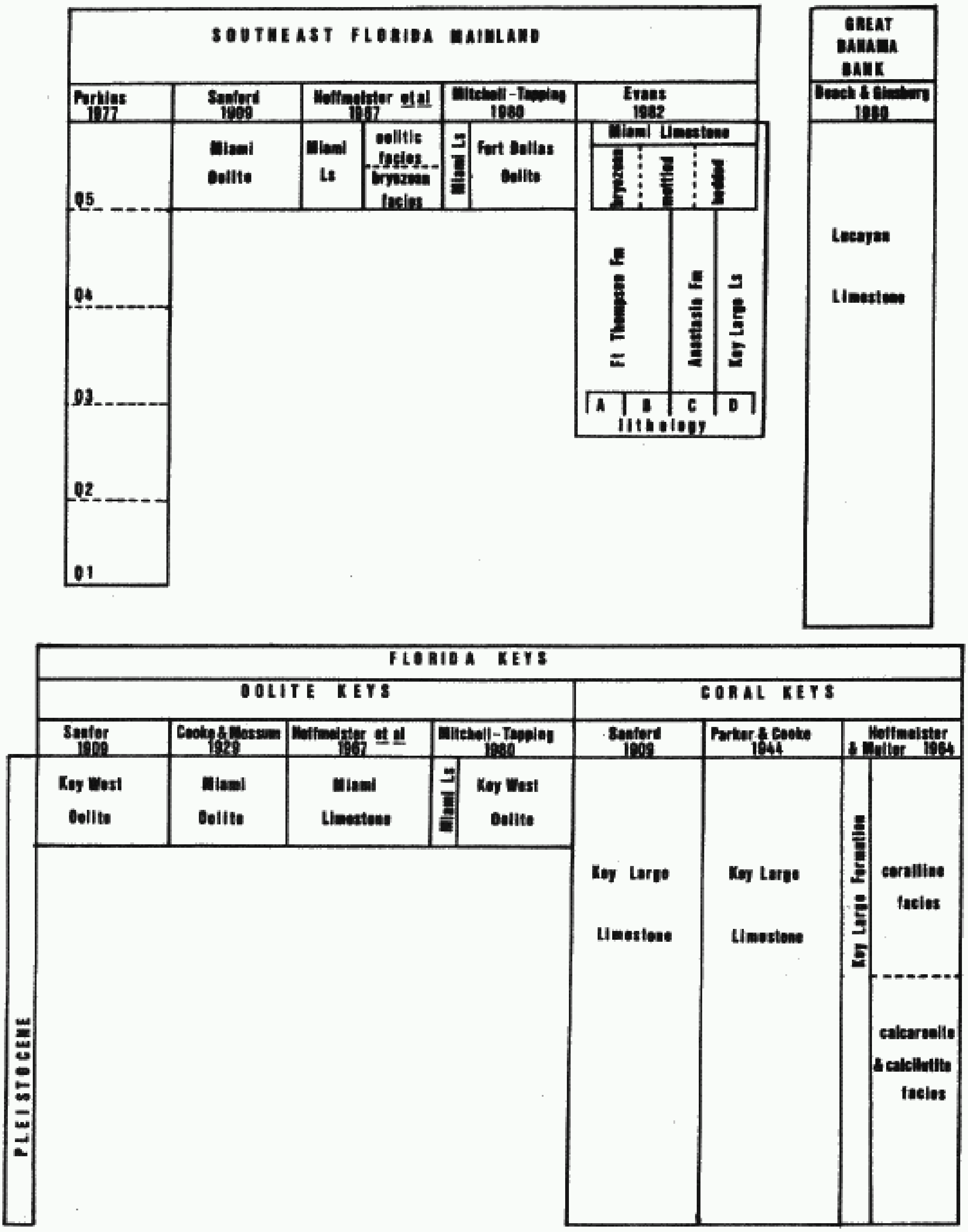

Figure 62. A chart of the stratigraphic nomenclature for the late Pleistocene of peninsular Florida (Evans, 1982). The Ft. Thompson, Key Largo, and Anastasia Formations underlie the Miami Limestone and only the upper portions of these formations are time equivalent to the Miami Limestone as outlined in figure 1. Note the actual time equivalence of the uppermost Anastasia Formation and the Miami Limestone are not shown by this chart. The chart is an expansion of the one presented by Perkins (1977).

APPENDIX II
Additional Stops

1. Rickenbacker Causeway, 50 m west of toll booths, south side of road: meter-high outcrop exposes foresets dipping N. 15° W. overlying burrowed facies; contact is undulating package (first-order) boundary exhibiting about 0.5 meters of relief.
2. Brickell Avenue and SE 15th Road: meter-high outcrop exposes 45-cm-thick foresets dipping due north at 26°; foresets overlie burrowed facies containing burrows of Callianassa sp., burrowing anemonae, and horizontal sediment feeders, among others.
3. 1642 Brickell Avenue, west side of road: clasts of oolite (up to 30 cm in diameter) in oolite matrix overlying very sharp (lithified?) erosion surface with about 0.5 meter of relief. Numerous West Indian top shells.
4. 132nd Street and Old Cutler Road, boulders along east side of road: burrowed, vuggy Miami Limestone.
5. 120-160 SW 10th Street, south side: package boundary separating cross bedded channel filling from underlying burrowed limestone; dip directions change from S. 70° E. on west side to N. 10° E. on east side of outcrop; 7-meter-wide channel exposed in N-S outcrop along driveway on west side of building at 160 SW 10th Street; sea cliff in west part of yard at 120 SW 10th Street.
6. 3rd Avenue and SW 7th Street: west and south of apartments on southwest corner, first-order bounding surface separating channel fill from well burrowed lower unit; south of apartments on southeast corner, first-order bounding surface with ripple-laminations preserved at contact between foresets.
7. U.S. 1 and 112th Street, Kendall Veteran's Wayside Park: 2-meter-high exposure of burrowed facies with small notch developed at water table.
8. U.S. 1 and 160th Street, small part on east side of U.S. 1: total exposure about 2 meters high, lowest half-meter burrowed facies, one meter cross bedded and uppermost half-meter burrowed; dips in cross-bedded unit very variable, generally to southeast but including some which dip due N and others due S. A few westerly dips in uppermost unit where it is not burrowed; dips generally 25° or less.
9. 72nd Avenue and 124th Street, west side of 72nd Avenue: beautifully exposed cross beds, planar-tabular, second-order bounding surfaces may be traced for 30 meters, dips 25°-30°, due south to 20° E or W of south, anemonae burrows crossing sets.
10. Along the shore of Biscayne Bay at east terminus of 168th Street, turn south, about 100 m turn east along wall of Deering Estate: south of estate virgin mangrove swamp and karst surface; site of Kohout's 1960 study of mixing zone; karst may be result of dissolution in mixing zone prior to lowering of water table.
11. Biscayne Bay, shoreline east of about 1600 Brickell Avenue (requires boat for access): small segment of undisturbed shoreline where Biscayne Bay laps against base of Silver Bluff; burrowed facies (horizontal sediment feeders) in sharp contact overlying cross bedded facies; well developed sea-level notch as much as 2 meters deep.

12. Coral Gables Waterway (requires small boat): walls of waterway expose varying foreset directions and transition to burrowed facies on the interior of broad shoals in the vicinity of U.S. 1.
13. McFarlane Avenue, Coconut Grove: outcrops on south side of road, topographically near top of barrier bar, low-angle cross bedding dipping seaward in uppermost beds, some oolite clasts in cross bedded oolitic matrix.
14. Monkey Jungle, 14805 SW 216 Street, Walkway through primate zoo leads over natural karst surface and by several solution-collapse pits up to 3 meters deep.

APPENDIX III
Estimate of Surface Dissolution

Assume <u>all</u> Ca^{++} in groundwater is derived from dissolution of $CaCO_3$ by rainwater. This is a maximum value because some calcium is probably derived from sea spray, fertilizers, and septic tank effluents, among other sources.

Groundwater contains about 80 ppm Ca^{++} (Parker, Ferguson, and Love, 1955; Pitt, 1974). It was derived from the dissolutionn of about 200 mg $CaCO_3$ in each liter of water.

At present, each year every cm^2 of the surface of the Miami Limestone is exposed to about 150 cm^3 of water. Throughout most of its history, however, rainfall was much less than this (Gleason and others, 1974; Watts, 1975; Moran, 1975), perhaps intermediate between the dry and wet seasons, let's say 75 cm^3 of water each year, although several authors suggest a climate much more arid than this. Also, most of the rainfall evaporates either before reaching the water table or directly from the water table through evapotranspiration. Estimates of evapotranspiration suggest it is about 78 percent in the Miami area (Dohrenwend, 1977), leaving about 16 cm^3 of water to dissolve limestone each year. Of course, evapotranspired water may dissolve limestone but it is redeposited on evaporation. Because the limestone was deposited 120,000 years ago, this amounts to 1980 liters of water reacting with each cm^2 of surface of the Miami Limestone. At 200 mg/liter, this water removed 396 gms of rock. Using an average density of 1.5 gm/cm^3 for the Miami Limestone, this amounts to possible removal of 264 cm of rock from the surface <u>if all dissolution were concentrated at the surface.</u> This, of course, is not the case. In fact, most dissolution probably takes place below the surface after rainfall has had time to equilibrate with CO_2-rich soil gases. If we guess that about half the total dissolution occurs at the surface, then about 132 cm of rock has been removed from the Miami Limestone.

It is interesting to note that on topographically high areas rain falls directly on limestone, and in the low areas water often percolates through a meter or more of soil before reaching the limestone. This may cause dissolution to be more concentrated at the limestone surface in depressions, selectively deepening those areas of Miami Limestone that are overlain by soil.